Water Resources Research Center
Annual Technical Report
FY 2014

Introduction

When compared to population centers in continental areas, water shortages and quality problems are more critical in Hawaii and the Pacific because of their geographic isolation and small land areas. Owing to their spatial and temporal scales, the Hawaiian Islands can serve as a microcosm of what may already be a reality for many areas in the world that share similar water supply and quality problems. Over the past 50 years, since WRRC was established, the research focus mainly addresses the following general categories.

- Groundwater Characterization Assessment and Modeling
- Groundwater Contamination, Drinking Water Supply Protection
- Recreational/Microbial Water Quality, Microbial Methods
- Wastewater Treatment Technology
- Wastewater Reuse/Disposal
- Watershed/Non-Point/Runoff
- Ocean Outfall Biomonitoring
- General Marine Water Quality
- Economics/Policy/Law
- Climate/Atmosphere/Precipitation/Evaporation/ Flooding
- Rainwater Catchment
- Streams/Lakes

In addition to basic research, many of the studies have aimed at solving specific water resource problems, such as biomonitoring near ocean outfalls, arsenic contamination, and rise in well nitrate level. Others have been initiated to meet federal regulations/obligations, including biomonitoring, source-water assessment program, and watershed protection plan.

Research Program Introduction

The Hawaii's Water Resources Research Center (WRRC) has continued to address issues related to water demand and quality problems critical to Hawaii and the Pacific, including American Samoa. When compared to continental areas, such issues are more critical because of these areas' geographic isolation and small land areas. The research covered in this report include groundwater characterization and modeling, water resource contamination, recreational chemical and microbial water quality, microbial methods, wastewater disposal and ocean biomonitoring, evaporation, and ecological and environmental climate-change effects. In addition to addressing important basic research, many of the studies were aimed at solving specific water resource problems. In 2013, WRRC was given the added responsibility as the WRRIP Center for American Samoa. This report emphasizes the efforts to establish research studies dealing with this Territory's water demands, water quality and land-ocean interactions. The following sections summarize the research efforts for the reporting period grouped into main categories.

Microbial Studies

The safety of Hawaii recreational waters is a critically important factor in attracting tourists to Hawaii and in maintaining the lifestyle enjoyed by residents. The current monitoring system uses a number of enterococci as an indication of sewage contamination and an increase risk of illness. Despite the apparent lack of sources of sewage, the beach water in Hawaii sometimes exceeds the Environmental Protection Agency standards for safe use. Past research conducted by scientists at WRRC revealed that even in the absence of sewage, the fecal indicator bacteria can grow and reproduce in soils under tropical conditions. This significant finding led Hawaii state regulators to adopt other more appropriate indicators of fecal pollution, such as the bacterium *Clostridium perfringens*. Results of the research with *C. perfringens* have proven applicable to other tropical areas and even to some temperate regions. Findings in Hawaii have also led other scientists to conduct studies examining the natural prevalence of indicator organisms in the environment and their appropriateness as indicators of sewage contamination in recreational waters.

WRRC has continued to advance microbially related research during this reporting period. One project deals with the evaluation of a rapid qPCR method for enterococci. Of the 151 coastal samples collected from 2013 to 2014 from 12 beaches on Oahu, only a single sample did not comply with the enterococcus and *C. perfringens* based recreational water quality standards. In contrast, analyses of 117 samples collected during the same timeframe from the Manoa watershed indicate possible sewage related impairment in the urbanized section of the watershed. If used simultaneously, human *Bacteroides* and human polyomavirus markers are suited for microbial source tracking purposes in Hawaii. Distribution of the source specific markers and *C. perfringens* in the coastal and watershed samples indicates that *C. perfringens* is a reliable sewage indicator and justifies its use as a water quality standard in Hawaii. The qPCR method was compared to two currently accepted culture based methods for recovery of enterococci from a variety of environmental waters. While rapid methods are urgently needed and offer great promise, in its current form, the rapid qPCR method for enterococci (USEPA Method 1611) cannot be used in Hawaii due to the compounds that interfere with PCR reactions. This inhibition results from rapid DNA extraction protocol and appears to be associated with coastal waters but not with inland waters of Hawaii. The number of enterococci obtained by all three methods and the presence of two molecular markers specific for sewage were evaluated based upon the current water quality standards.

Another project deals with the evaluation of next-generation sequencing technologies for environmental monitoring. The scope of the research covers the characterization of microbial communities from wastewater plants and selected beaches of Hawaii using a metagenomics approach. This study catalogued the microbial diversity in the wastewater treatment plant (WWTP) discharges and the coastal environments on Oahu. Samples were collected from four Oahu WWTPs (Hawaii Kai, Honouliuli, Kailua, and Sand Island) and from

coastal waters extending from the Sand Island outfall to Waikiki. Using a novel primer set, the sample library was compiled targeting larger and more informative fragments to fully benefit from the recent advantages in sequencing technologies. The archived results include over 1,000 microbial isolates. Sequence analyses are ongoing. The major goal of this project is to establish a research program to bridge environmental and public health sciences by leveraging novel community analyses tools to target environmental and human health concerns collectively. The results will hopefully provide a more holistic view of the coastal ecosystem and promote sustainable development.

The final project in this category is the evaluation of the Portable Multi-use Automated Concentration System (PMACS) for the analysis of indicator bacteria and microbial source tracking markers in Hawaii. Overwhelming evidence exists that microbial distribution is “patchy.” The small sample volumes (usually 100 mL) used in routine microbial water quality monitoring programs do not provide an adequate representation of the water quality nor are they usually sufficient for the detection of human pathogens. An analysis of larger sample volumes is necessary. In this study, wastewater, drinking water, and beach water samples were collected at various locations on Oahu by teams from WRRC, Hawaii Department of Health, City and County of Honolulu, and The University of South Florida. The analyses confirms that PMACS is a practical and economical tool for concentrating a wide variety of microorganisms from large sample volumes (larger than 100 L) and can provide a more comprehensive characterization of microbial water quality. The potential use of the instrument has generated about $50,000 in support from the Hawaii Department of Health and a private sponsor to purchase and apply PMACS to resolve microbial water quality issues in Hawaii.

Ocean and Ocean Outfall Biomonitoring

Waste disposal for the Island of Oahu is done through ocean outfalls that discharge the effluent in deep water far offshore. As a condition of obtaining advanced treatment waivers, the City of Honolulu was obliged to conduct monitoring of the ecosystems around the plant outfall pipes, which is done under WRRC supervision. The research team has continued to assess the health and changes to communities of organisms (fish and sandwelling worms, crustaceans, and mollusks) around the outfalls at Sand Island, Barbers Point, Mokapu, and Waianae for more than twenty years. The methodology developed by the team in has been applied in other tropical locations by these researchers. The dataset collected by this long-term project is unparalleled in terms of time extent, and project researchers have discovered a number of new species in the course of their work.

A related active project for this reporting period addresses temporal and spatial effects of sewage outfalls on the reproductive capabilities of polychaetes. The project is motivated by the need to understand the long-term effects of the sewage discharge on the marine ecosystem function and the reproductive capabilities of selected marine worms could provide a good measure of ecosystem health. This research aims to test the hypothesis that there will be spatial and temporal differences in the reproductive capabilities of syllid polychaetes at different outfall locations. Reproductive data of polychaetes present in the reports of the Sand Island and Barbers Point ocean biomonitoring projects for a period of 11 years were used. Preliminary results using two of the most abundant species (i.e., *Pionosyllis heterocirrata* and *Sphaerosyllis* sp. G) show that both species reproduce year round and could be good indicators for ecological disturbances. There were no significant differences in the reproductive capabilities of these two species in samples collected near and far field from the outfall diffusers and throughout the 11-year period. Temporal differences seem to be more accentuated than spatial differences. The next step would be to increase the number of species and perhaps to perform additional analysis using the environmental variables available (e.g., chemical characterization of the sediments and grain size) and verify if the reproductive success is correlated to any of them.

Another project is dealing with building a polychaete species database for water management purposes in American Samoa. Shallow water polychaete species were characterized qualitatively at twenty sampling stations around the Island of Tutuila. The intent was to determine the polychaete species present in soft

sediments, diverse algal assemblages, and coral rubble to provide a polychaete species list that would be useful for future biomonitoring projects. The shallow water polychaetes of American Samoa are very diverse with a total of 546 individuals collected in this study representing 26 families and 73+ species. At least one new species was collected from samples taken from this project and will be formally described and named. The species *Hydroides elegans*, *Dipolydora socialis*, *Salmacina dysteri*, and *Sabellastarte spectabilis* were probably transported to American Samoa and are accidental introductions. Impacts of these species have been reported in other regions of the Pacific Ocean. This research characterizes the first comprehensive study aimed to taxonomically describe and identify the polychaete worms around the Island of Tutuila. All specimens will be added to the collection at the Bernice Pauahi Bishop Museum and then made available for future researchers working on water quality and the effects on the benthic macrofauna in American Samoa.

Hydrology

A hydrology related project deals with the determination of groundwater fluxes and evaluation of the effectiveness of low-permeability valley-fills in the Pearl Harbor Aquifer, Oahu. The study was motivated by the fact that the majority of groundwater used on Oahu is withdrawn from the aquifer. Successful water-resource management therefore needs an accurate understanding of the groundwater flow through the aquifer and quantification of fluxes to the aquifer from adjacent groundwater areas. Accurate assessment also requires evaluating the effects of local hydrogeologic features, in particular low-permeability valley-fill barriers, including those associated with Waimano, Waimalu, and Kalauao Streams. A regional numerical groundwater model was developed to address these needs. Oahu's complex geologic structure was reduced to three hydrogeologic units: 1) dike-intruded volcanic rock, 2) dike-free volcanic rock, and 3) sediments and rejuvenated volcanics. The altitude of the contact between overlying sediments and volcanic rock was generated to facilitate model grid generation. Measured water levels on Oahu from various sources were compiled to calibrate the model. To date, results have not been finalized because the USGS recharge estimates for Oahu have only recently been updated.

Detailed estimates of hydraulic properties are important for models that are used to assess groundwater availability and quality. A project covered by this review period assesses hydraulic properties through tidal groundwater-level analysis for the state of Hawaii. Such analysis is feasible, considering that the attenuation of tidal variations in groundwater levels with distance from the coast reflects such properties. The study presents a regional compilation of tidal-attenuation information for the State, and estimates hydraulic properties using groundwater-level records from more than 250 wells in volcanic rock and more than 200 wells in coastal sediments. Results are combined in a regional context with respect to the hydrogeologic framework of each island. The tidal response in groundwater levels can help to distinguish and identify hydrogeologic units. For example, in general, no tidal signal was observed in dike-intruded volcanic rock, and the lower-permeability coastal sediments caused a damping effect of the tidal signal. Aquifer-diffusivity and hydraulic-conductivity estimates in dike-free volcanic rock decrease with increasing island age, which is consistent with a reduction in permeability through weathering. The results will be useful for developing island-wide numerical groundwater models and are implemented in an ongoing USGS regional volcanic-rock aquifer study.

The volcanic-rock aquifers of Oahu supply freshwater to the growing population on the island, but resources are limited and particularly susceptible to impacts from human activity through land-use changes or excessive withdrawals and climate change. Assessment of groundwater availability in the volcanic-rock aquifers of Oahu, Hawaii, is timely with the availability of new information and technologies. Updated recharge and hydrogeologic information and improvements on groundwater modeling approaches are combined with the desire to consider effects of climate change will lead to a better assessment of groundwater availability. A numerical modeling analysis of the most developed regional groundwater-flow system in the main Island of Hawaii updates knowledge of the availability and sustainability of Oahu's groundwater resources, and provides insight into the impacts of human activity and climate change on groundwater resources. Oahu's

complex geologic structure was reduced to three hydrogeologic units: 1) dike-intruded volcanic rock, 2) dike-free volcanic rock, and 3) sediments and rejuvenated volcanics. Measured water levels, midpoint of the transition zone between fresh- and saltwater depth data, base flow and Pearl Harbor spring-discharge data on Oahu for recent conditions (2001–2010) were compiled to calibrate the numerical model. The analysis is part of an ongoing USGS regional volcanic-rock aquifer study.

Hydrology related studies also include a project dealing with quantifying groundwater discharge from the Faga'alu Aquifer, American Samoa. Faga'alu valley on Tutuila Island has been designated as a priority watershed management area by the NOAA Coral Reef Conservation Program. While Faga'alu's surface water is on the AS EPA 303(d) list of impaired waters (CRCP 2013), at present, there is no information available regarding groundwater-derived pollution in the valley. This study's focus is on evaluating surface-water-groundwater interactions within Faga'alu Stream and to quantify the rates of groundwater to the stream and submarine groundwater discharge into Faga'alu Bay. The fieldwork completed in the summer of 2014 showed a close connection between stream water and groundwater. Baseflow is a significant contributor to stream flow and to coastal groundwater discharge. Stream samples show an increasing trend of total nitrogen concentrations as well as $d^{15}N$ values as the stream travels through developed areas. This indicates the input of nitrogen to the stream is most likely derived from human or animal waste products.

Another project traced the interconnectivity between high-level and basal groundwaters in the west side of the Island of Hawaii. The project was motivated by the recent rapid development in the North Kona District of West Hawaii that has raised concerns regarding the sustainability of the region's groundwater resources in the face of increasing demand. A large portion of the region's municipal water supply is withdrawn from wells tapping a high-level groundwater system. However, information is lacking regarding the effects of withdrawals from this high-level aquifer on the underlying and adjacent basal groundwater system. Such a system sustains the region's unique coastal ecosystems while at the same time being utilized for municipal, industrial, and irrigation purposes. While the abrupt freshening and rapid rise in the elevation of the inland higher-level waters clearly indicates that these strategic aquifers are distinct, the nature of their divide and, importantly, the degree of connectivity between their water masses remains uncertain to completely unknown. Groundwater is withdrawn from both of these sources, but due to dramatic increase in needs for potable supplies, a large and ever increasing portion of the region's municipal water supply is withdrawn from wells tapping the high-level groundwater system. Additionally, the effects of increased development—including industrial, agricultural, and waste disposal activities—on groundwater quality in this area are also poorly known due to both a lack of water quality data and a lack of understanding of the region's subsurface hydrology.

Recent studies of West Hawaii groundwater have suggested that the high-level groundwater system in the Kona area does drain into the basal lens and that a substantial portion of coastal basal groundwater originally fell as rain in the upland regions of Hualalai volcano and Huumula Saddle. Yet, recent proposals for land development have implied that relatively impermeable barriers may separate these waters. This project was thus designed to examine the degree of hydrologic connectivity between the high-level and basal aquifers within the North Kona (North Keauhou) district of Hawaii. The research proposed here is needed to test such disparate hypotheses and to fully evaluate the proportion of mixing that occurs between these critical aquifers. To achieve this goal, the project used end-member mixing analysis of 2H and 18O in precipitation, wells, coastal springs, and ocean waters as tracers with which to evaluate the North Kona groundwater connections. The principal finding of this analysis was that basal groundwater in the Keauhou aquifer does, in fact, contain a significant and quantifiable portion of recharge from the high-level aquifer. This finding has attracted a great deal of interest from, and value to, stakeholders and government agencies in the debate regarding the designation of the Keauhou aquifer, and was later validated by the published results of Tillman et al. (2014), which used this project's methodologies to come to the same conclusions.In addition, the most recent data has been used in updated basal groundwater mixing scenarios that were provided to staff of the Commission on Water Research Management (CWRM) to assess the validity of various conceptual models of groundwater

flow in the Keauhou aquifer. Additionally, the data acquired by this study has been utilized in presentations by experts during CWRM contested case hearings regarding the designation of the Keauhou aquifer as a special management area in late 2014. This project's data is also currently being utilized by the staff of the Hawaii Department of Health to develop a new model of groundwater flow in West Hawaii for the purpose of evaluating source water protection.

A third hydrology related project assessed groundwater sustainability of the Island of Tutuila, American Samoa, which is currently faced with multiple water resources challenges. Groundwater sources provide the majority of drinking water to the island's approximately 57,000 residents, and a number of wells in the island's most productive aquifers are suspected to harbor contamination from quickly infiltrating surface pollutants, including contaminants associated with automobiles, biological pathogens, and nutrients pollution from poorly constructed human and pig waste disposal systems. This study uses groundwater modeling and field geochemical observations based on water quality sampling aimed at a better understanding of Tutuila's water contamination issues and identifying potential contaminant sources and groundwater recharge timescales. These results are intended to assist water resource managers in determining best management practices (BMPs), which will ensure the continued sustainability of groundwater resources on Tutuila. Preliminary results indicate that on-site wastewater disposal systems are a likely cause of elevated nutrient concentrations in the island's most developed aquifers. The study is also examining the potential for development of new water resources in other aquifers that are up gradient of contamination sources.

The final project in this group deals with evaluating of the impact of drought conditions upon the Waiahole Ditch System development tunnels, with the ultimate aim of assessing groundwater sustainability implications under adverse climate change conditions. This ditch is located upland in the Koolau Mountains and taps water believed to be stored in dike compartments. The Pearl Harbor aquifer is located downstream on the western/southern slopes of this mountain range and is an extensively used basal aquifer with major withdrawals by the Department of Defense and the Honolulu Board of Water Supply. This aquifer is of prime significance to the sustainability of the island of Oahu. The specific objective of this study is to define the relationship between high-level dike compartments and the down-gradient recharged Pearl Harbor aquifer. Data has been compiled and is being updated to study the overall sustainability of the study area. During this reporting period, the automatic recording sensors that had been set up the in ditch system earlier were retrieved and some data were recovered. Statistical and spatial relationships are being explored in the various datasets collected. In addition, base flow discharges will be evaluated by using climatological data during past episodes of drought. Univariate multiple regression models will be used to evaluate the relationship among predictor variables (rainfall distribution, tunnel base flow discharges, Pearl Harbor groundwater production), and response variable (monitored wellhead levels). Semi-partial correlations will be used to identify the unique contribution of predictor variables upon a response variable. It is expected that a historical analysis of significant drought episodes will offer an insight into future adverse climate changes upon groundwater sustainability and will be useful to the water utilities and future planning.

Sustainability

Hawaii faces immediate challenges in meeting the demand for safe drinking water and the management of wastewater. Despite the State's location in the middle of the Pacific Ocean, water resources are very limited and Hawaii's ecosystems and environments are increasingly threatened by drought and the impacts of environmental degradation and climate change. To emphasize the important role of WRRC in serving the State's conservation efforts, a water literacy project was initiated that is aimed at addressing complex human-environment interactions associated with water resource management, as mediated by the diverse cultural, political, and economic conditions in the State of Hawaii. In particular, the project focuses on educating the University of Hawaii at Manoa campus community to raise literacy about water-related issues at the campus, neighborhood, watershed, and island scales.

Climate and Climate Effects

Climate related studies include developing monthly rainfall maps for the islands of Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii, 2008–2010. Efforts are hampered by the fact that the Hawaiian Islands have one of the most diverse rainfall patterns on earth. Knowledge of the rainfall patterns is critically important for a variety of resource management issues, including groundwater and surface-water development and protection, controlling and eradicating invasive species, protecting and restoring native ecosystems, and planning for the effects of global warming. Currently, there is a set of monthly rainfall maps for the main Hawaiian Islands, however, the maps only cover up to 2007. In recent years, it has become apparent that monthly maps for the period of 2008 to 2010 are needed for numerous water-resource investigations being undertaken by federal, state, and county agencies in Hawaii. Recent rainfall station data was collected from over 10 networks and monthly rainfall maps were produced from 2008–2012. These maps are available for download in raster GIS format. The maps extend the available rainfall record through 2012 to enable analyses of more recent hydrological conditions in Hawaii.

A climate related study deals with an improved methodology to estimate evapotranspiration. Recently, a number of studies have focused on estimating surface turbulent heat fluxes via assimilation of sequences of land surface temperature (LST) observations into variational data assimilation (VDA) schemes. Using the full heat diffusion equation as a constraint, the surface energy balance equation can be solved via assimilation of sequences of LST within a VDA framework. However, the VDA methods have been tested only in limited field sites that span only a few climate and land use types. Hence, in this study, combined-source (CS) and dual-source (DS) VDA schemes are tested extensively over six FluxNet sites with different vegetation covers (grassland, cropland, and forest) and climate conditions. The CS model groups the soil and canopy together as a single source and does not consider their different contributions to the total turbulent heat fluxes, while the DS model considers them to be different sources. LST data retrieved from the Geostationary Operational Environmental Satellites are assimilated into these two VDA schemes. Sensible and latent heat flux estimates from the CS and DS models are compared with the corresponding measurements from flux tower stations. The results indicate that the performance of both models at dry, lightly vegetated sites is better than that at wet, densely vegetated sites. Additionally, the DS model outperforms the CS model at all sites, implying that the DS scheme is more reliable and can characterize the underlying physics of the problem better.

The reporting period also covers a project dealing with forecasting climate change impacts on watershed-based ecosystem services in Hawaii. The study is motivated by climate change, which is expected to have significant impacts on native threatened and endangered bird species, particularly in terms of habitat alteration. Understanding and modeling these impacts in a manner that is useful for decision-makers or management is difficult since many empirical modeling frameworks require large amounts of long-term data that can be costly to collect. To address this, the project proposes a decision support approach to understanding climate change impacts on the habitat, life history functions, and abundance of endangered bird species by coupling regional watershed simulation models (e.g., AnnAGNPS) under Intergovernmental Panel on Climate Change (IPCC) defined scenarios and expert knowledge-based models of bird ecology. To test the proposed approach, the project staff uses data from the Hawaiian Stilt, Hawaiian Coot, and Hawaiian Moorhen populations, and watershed data from the Island of Kauai as a case study. The type of decision framework the study proposes provides wildlife managers a low cost approximate understanding of the dynamic interaction of climate change, habitat and wildlife ecology based on pooling available expert knowledge and existing data about watershed projections. Model results based on IPCC scenarios suggest that increased precipitation will increase Stilt abundance, but decrease Coot and Moorhen abundance. On the other hand, decreasing precipitation may have similar effects across all three species. Additionally, the adopted integrated model scenarios suggest that climate change will differently impact life functions (e.g. parental success, breeding, foraging success, etc.) across the three species. Combining empirical and expert-based conceptual models allows managers to understand the local ecological impacts associated with global climate change, making it relevant to the management scale. Additionally the study concludes that this framework can

be easily employed by wildlife managers to understand the impacts of climate change on different types of animals and across different ecological conditions. This project was leveraged for additional funding (University of Hawaii Sea Grant) to extend this project's novel modeling method to other communities and resource management in Maui, which provided a PhD student two additional years of funding.

Climate change effects were also the motive for another project that deals with assessing the impacts of stream flow rate on food resource quality and diets of native species in Hawaiian streams. Rainfall and stream flow are being altered by anthropogenic impacts such as climate change and water diversions throughout Hawaii, which may affect food resource quality and quantity available to stream macroinvertebrates. This includes the native and endemic amphidromous atyid shrimp or 'opae kala'ole (*Atyoida bisulcata*). A rainfall/stream flow gradient along the North Hilo coast on Hawaii Island provided a model system to examine the potential impacts of altered stream flow on food resource quality and quantity, and how these impacts can affect the diet and feeding modes of *A. bisulcata*. The researchers sampled *A. bisulcata* and 10 potential food resources in five streams that vary in stream flow across the gradient. Analysis of the stable isotope signatures ($d^{13}C$ and $d^{15}N$) and C:N ratios revealed the highest quality (most nutritious, with respect to C:N) food resources available (i.e., biofilm and chironomid larvae Chironomidae) as the primary contributors (largest percent contributions) to the diets of *A. bisulcata* across the gradient, regardless of flow metric or mean annual rainfall (MAR). Secondary contributors (i.e., food resources that contributed to < 20%) to shrimp diets changed from pelagic (filamentous algae; and fine and course particulate organic matter [FPOM and CPOM, respectively]) to benthic (leaf bacteria, and fine benthic organic matter [FBOM]) food resources as flow decreased. These resources were slightly lower quality than biofilm and chironomids across the gradient. Total weighted C:N (combined biomass and C:N) of all resources sampled declined with decreasing stream flow, driven mainly by increased biomass of two resources that are not considered contributors to the diets of *A. bisulcata*: low quality leaf litter in low flow streams and high quality moss in high flow streams. Quantity (biomass and/or total stock) of high quality biofilm, chironomids, FPOM, and CPOM, declined significantly with decreasing stream flow, which is probably influencing the patterns in decreased fitness in *A. bisulcata* also observed in streams across this gradient. This study highlights the need to develop management strategies to maintain stream flow levels to support healthy communities of native stream fauna, and that additional research is needed to identify instream flow values that are based on impacts to ecological function (diet, reproduction, growth) rather than simply the presence or absence of species.

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Assessing Ground Water Sustainability of the Island of Tutuila, American Samoa

Basic Information

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Project Number:	2013AS424B
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Congressional District:	1
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Focus Category:	Water Quality, Hydrogeochemistry, Non Point Pollution
Descriptors:	None
Principal Investigators:	Aly I El-Kadi, Henrieta Dulaiova, Craig R Glenn

Publications

There are no publications.

Problem and Research Objectives

The Island of Tutuila in the territory of American Samoa is currently faced with multiple water resources challenges. A number of wells in the island's most productive aquifers are suspected to harbor contamination from quickly infiltrating surface pollutants, including contaminants associated with automobiles, biological pathogens, and nutrients from poorly constructed human and pig waste disposal systems (ASEPA 2006). Existing well development has already encroached on the upper boundaries of the developable basal aquifer and Tutuila's unique hydrogeology makes finding appropriate well sites above areas of potential contamination a difficult task (ASPA 2013). Currently, groundwater sources provide the majority of drinking water to the island's approximately 57,000 residents (ASEPA 2013). The island consists of two main geographic regions: (1) an eroded volcanic mountain range, and (2) a geologically recent, and thus, very hydrologically conductive lava and ash plain (Figure 1). In the Tafuna-Leone Plain, septic tanks, cesspools, and piggeries lie proximal to the drinking water wells in a highly permeable unconfined aquifer (Davis 1963). Negative impacts on groundwater quality in this region have been observed and a better understanding of the sources and fluxes of contaminants throughout the aquifer is essential to assist the island's decision makers and water resource management.

This study uses multiple groundwater models and geochemical tools to assist water resource managers in determining the best management practices, which will ensure the continued sustainability of groundwater resources. Numerical modeling is being used to answer hydrogeological questions regarding future well sittings, sustainable-yield determinations, and salt-water-intrusion potential. Geochemical observations and ongoing water quality sampling are intended to improve our understanding of Tutuila's water contaminant levels and hot spots, to evaluate potential contaminant sources, and to estimate groundwater recharge timescales.

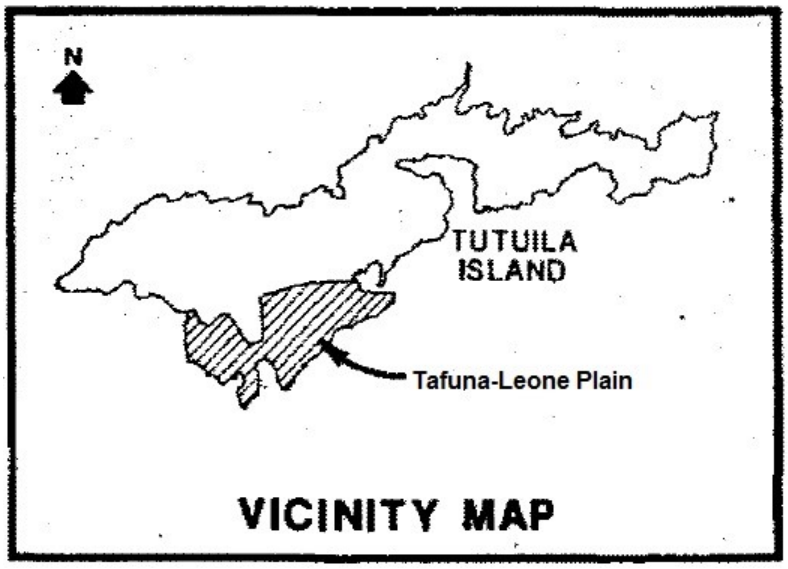


Figure 1. Regional geography of Tutuila. Modified from Kennedy/Jenks/Chilton (1987).

Methodology

Aquifer Testing

Recovery tests were performed on 26 American Samoa Power Authority (ASPA) production wells in summer 2014. These tests are useful for estimating aquifer properties, specifically transmissivity (T) and for comparing against results of pump tests (Kruseman and Ridder 1994). In addition, static water levels, which will be used for model calibration, were recorded at the end of the recovery tests. Tests were completed on active pumping wells with a manual water level tape and a vibrating wire piezometer/datalogger. Once stable pumping water levels were observed, pumps were shut off and recovery was monitored and recorded with the piezometer's data logger. Test durations were between four hours and five days. Recovery data were processed with the Cooper-Jacob Straight-Line Method (Halford and Kuniansky 2002) to estimate average values of T of the area of influence of each well.

Water Sampling

Water samples have been collected from nearly every production well on the island, from as many coastal/high-level springs as possible, and from selected streams. Sampling commenced in the summer of August 2013 and replicate samples from selected sites are presently being collected on a monthly basis. The majority of samples were filtered with 0.45 µm hydrophilic polyethersulfone capsule filters. Temperature, salinity, pH, and dissolved oxygen were measured in situ with a YSI multiparameter sonde (6600V2-2 model). Samples were collected in triple-rinsed acid cleaned 60 ml HDPE bottles and were immediately cooled for transport to storage facilities. Grab samples were analyzed the same day for dissolved radon gas concentrations and chilled samples were analyzed as soon as possible at the University of Hawaii laboratories for inorganic nutrients; total dissolved C, N, and P; major ions; δD and $\delta^{18}O$ of water; $\delta^{15}N$ and $\delta^{18}O$ of NO_3^-; and $\delta^{13}C$ of inorganic carbon.

Spring Mapping

Perennial springs and seeps are generally assumed to designate the location of the local water table and can therefore be inferred as a proxy for groundwater head elevations. During summer 2014, a number of high-level spring locations in the Malaeimi region (Figure 2) were identified and sampled for dissolved radon gas to test if springs represented true groundwater discharge, as opposed to recent rainwater. Radon is generally not present in surface water or precipitation, however, it is easily dissolved into groundwater from recoil and diffusion from aquifer material. Significant quantities of ^{222}Rn indicates recharge waters have been in aquifer pore spaces long enough for Rn concentration to increase by an order of magnitude or more (Figure 3). GPS coordinates were used to extract high accuracy spring elevations from a 1 m resolution DEM. Spring elevations were used as known head elevations for calibration of a steady-state MODFLOW model. Within the Malaeimi watershed, flux out to drains was routed back into the model via mountain front recharge at the applicable cells. Once calibrated, the model was used to run hypothetical water development scenarios to calculate sustainable yields for different geologic units within the model.

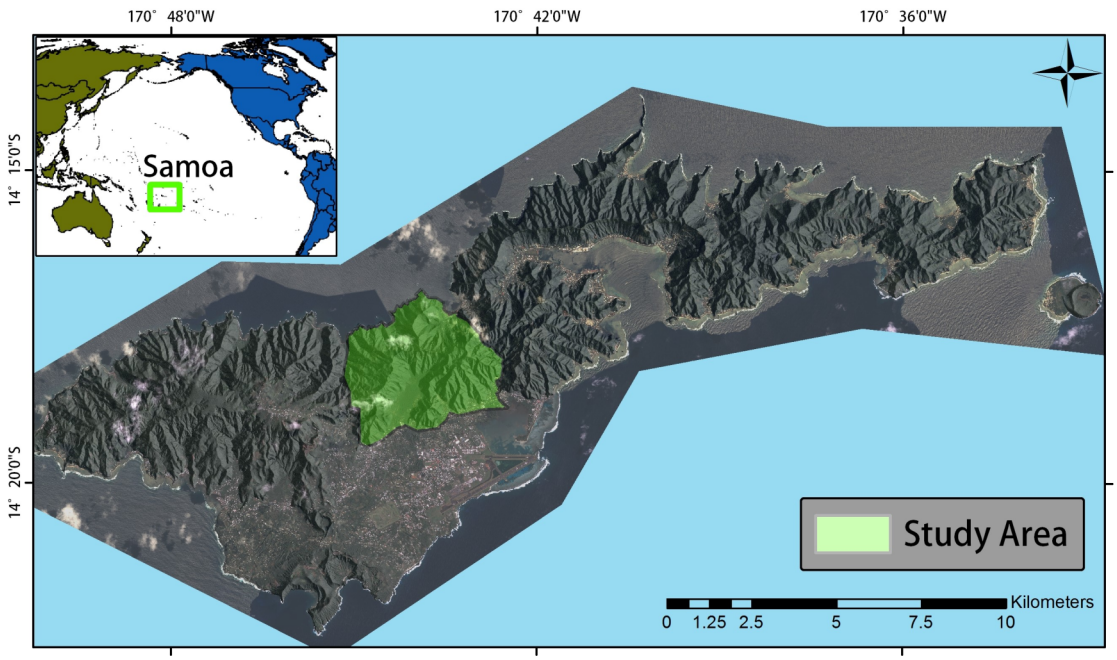


Figure 2. Malaeimi Valley modeling study area, American Samoa.

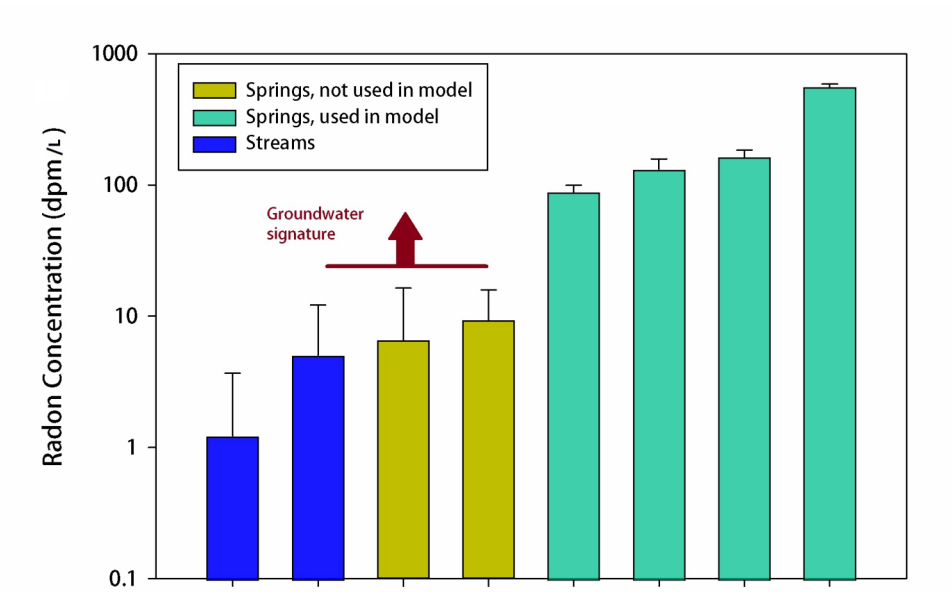
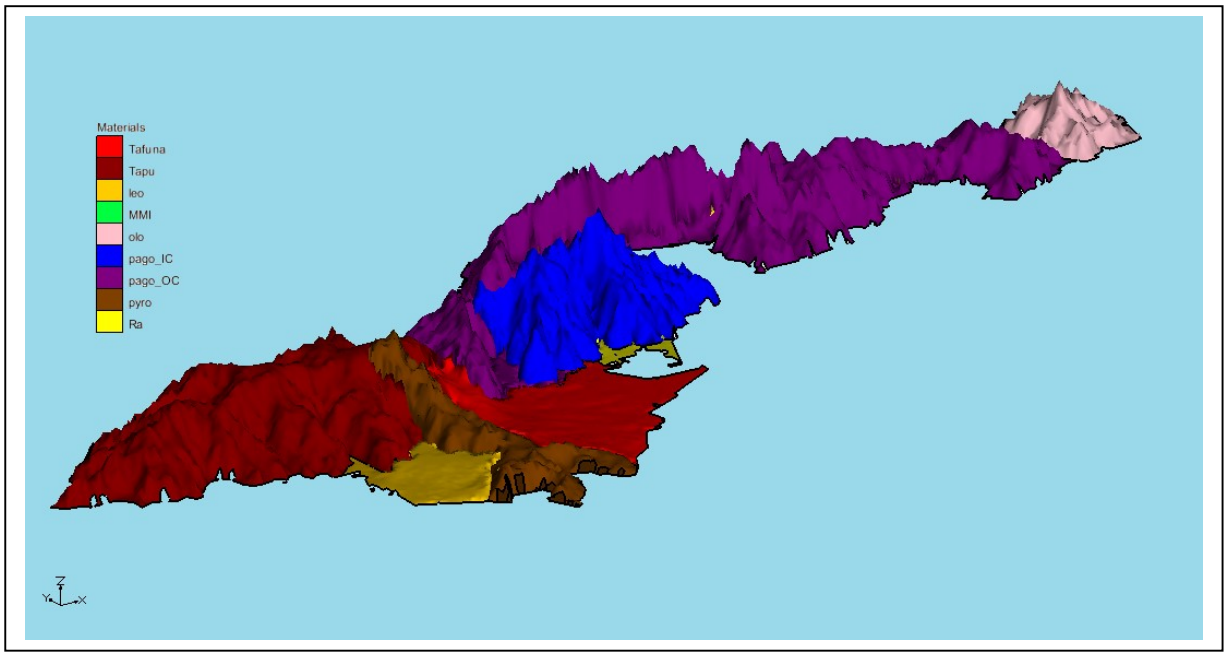


Figure 3. Concentrations of dissolved radon in springs used for model calibration were an order of magnitude greater than concentrations found in surface waters.

Measurement of Water Isotope δD and $\delta^{18}O$ Values

Monthly collection of samples for δD and $\delta^{18}O$ analysis of precipitation from four sites and groundwater from six sites has begun in August 2014. Groundwater samples are acquired directly from wellheads and precipitation samples are collected in cumulative precipitation collectors deployed at the same locations as the wells. The collectors used in this study are designed to prevent evaporation of accumulated rainfall and are based on collectors used for the same purpose by Scholl et al. (1996). Precipitation collectors and wells are sampled, and on-site rain gage data is downloaded on a monthly basis. Samples are sent to the Isotope Biogeochemistry Laboratory at the University of Hawaii Manoa for analysis.



Note: Units are based on geologic information and new aquifer test data.

Figure 4. Preliminary hydrogeologic units used for Malaeimi watershed.

Numerical Groundwater Modeling

Groundwater modeling is invaluable for efficient management and proper planning of water resource development. In addition to the aforementioned local scale model of Malaeimi watershed, new aquifer test and water level data are currently being used to infer aquifer boundaries and hydraulic conductivities for Tutuila's geologic units (Figure 4). This information is being integrated with well data from ASPA and climatological information to develop a regional-scale model of the whole island. Once this model is calibrated, it will also be used as boundary conditions for several local scale models focused on the Tafuna-Leone Plain and/or other alluvial-valley-fill aquifers. Once calibrated, these models will be applied to address a number of specific questions regarding contaminant fate and transport, the effects of climate change/variability, and the development of new water sources.

Principal Findings and Significance

Conceptual Model Development

Future efforts regarding hydrological investigations on Tutuila require an exhaustive quantitative resource. In this regard, a conceptual hydrological model is under development based on information from existing literature and preliminary data from this study. Information from past studies and government/industry reports includes drilling logs, historical pump tests, well-efficiency information, past modeling work, geological maps, and water quality results. New preliminary information includes updated water levels, results of pump and recovery tests, new water quality data, and results from a recent geophysical investigation. This resource will guide future modeling studies, well siting/exploration, and water resource management decisions.

Development of Collaborative Network of On-island Water Resource Stakeholders

Through this project, we have developed working partnerships with ASPA, American Samoa Environmental Protection Agency (ASEPA), American Samoa Community College (ASCC), as well as a number of working relationships with individual village leaders in the community. These relationships have involved sharing of water resource information, climatological and water quality data, as well as recommendations for project design and implementation on both sides. This project currently supports one faculty scientist and four student interns from ASCC.

Aquifer Testing and Numerical Modeling

A preliminary local scale numerical model was created for the area surrounding the Malaeimi watershed. This model was intended to synthesize data regarding surface hydrogeological features and to better understand the potential for high-level water development in Tutuila's mountains. Results from the local scale model of Malaeimi watershed indicate a greater potential for well development in the western portion of Malaeimi Valley than in the eastern part. The valley runs along the contact between dense ponded lava flows and trachyte intrusions of the Pago Pago inner-caldera unit on the eastern side of the valley and a'a lava and ash beds of the Pago Pago outer-caldera unit on the western side (Figure 5) (Stearns 1944). Based on model calibration results, hydraulic conductivity of the inner-caldera unit is roughly 12 times lower than that for the outer-caldera unit. In addition, modeled well-pumping rate to drawdown ratios are roughly 5 times higher in the denser inner-caldera region indicating there is a higher probability of success for a developable groundwater source in the outer-caldera unit of the Pago Pago shield.

Results of the aquifer tests in existing production wells yielded estimates for T in areas where water development has already occurred. Values of T in the Tafuna-Leone Plain were, as expected, significantly higher than those observed on other parts of the island. A number of wells in the plain did not appear to have any drawdown at all despite pump rates between 135–280 GPM. No clear explanation exists so far. Transmissivities on the Tafuna side ranged from 1,200 to 29,000 m^2/day and 6,100 to 17,000 m^2/day on the Leone side of the plain (Figure 6). These values confirm the presence of three hydrologic units with differing properties in the Tafuna Leone-Plain. In comparison, values of T from wells not on the plain ranged from 0.52 to 610 m^2/day. Values of T in the Taputapu shield were lower than those in the Tafuna-Leone

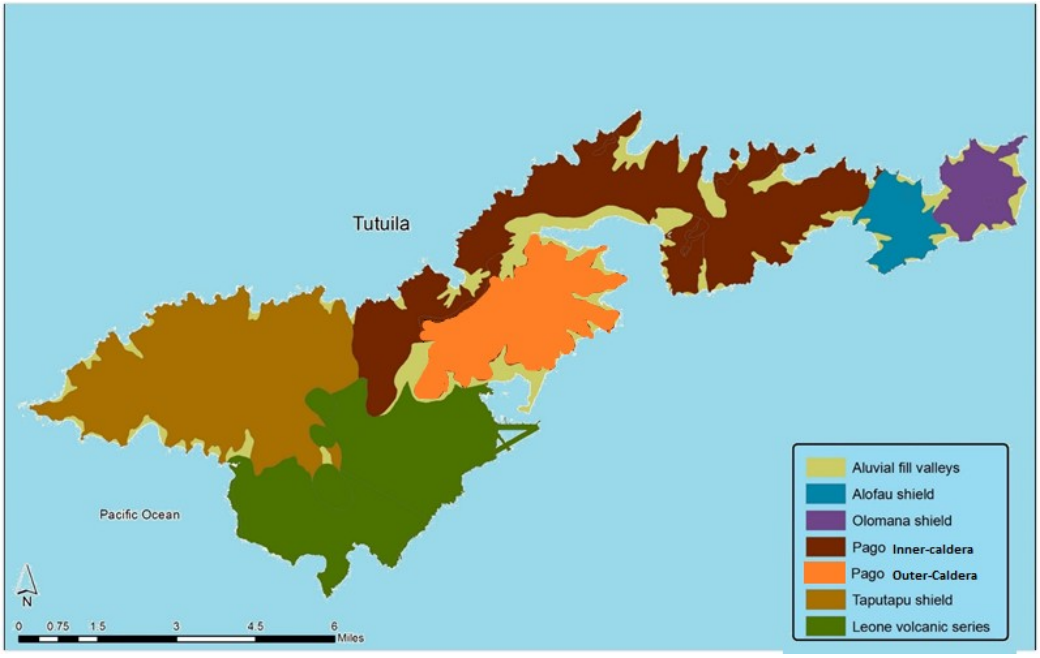


Figure 5. Primary geologic units based on mapping by Stearns (1944).

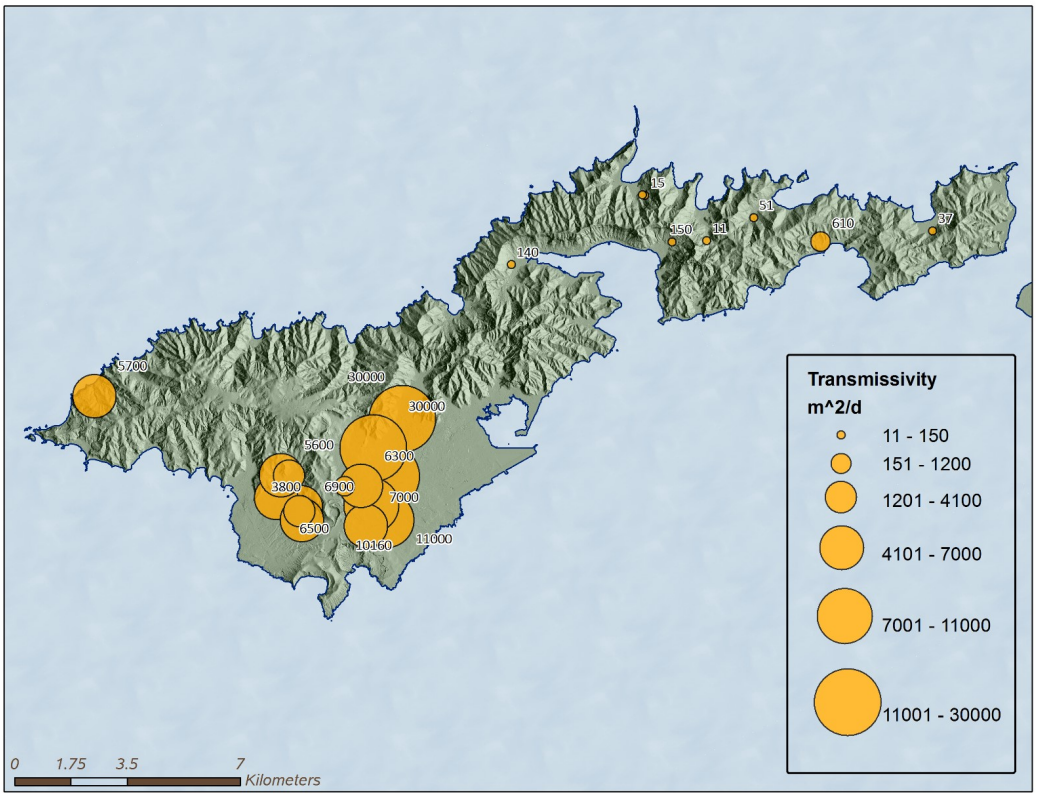


Figure 6. Estimated values of transmissivity based on recovery tests and analyzed with the Cooper-Jacob-Straight Line Recovery Method, Tutuila Island.

Plain but higher than those in the outer-caldera unit of the Pago Pago shield. This indicates the possibility that the basal lens of the Taputapu shield may have a higher degree of water resources developability than the Pago Pago shield.

Tafuna-Leone Water Quality

Municipal water on Tutuila has been unsafe to drink since 2009 due to detections of bacterial contaminants in the island's most productive wells (Chen 2013). The unconfined aquifer is highly permeable and is located below a well-mixed semi-urban landscape consisting of small-scale agricultural plantations, livestock operations, and areas of human habitation. Elevated levels of groundwater nitrate have been observed in the Tafuna-Leone Plain region and likely originate from three predominant sources: on-site disposal systems, domestic pig waste, and agricultural fertilizers. Analysis of $\delta^{15}N_{(NO_3)}$ shows an enrichment along groundwater flowpaths below developed areas (Figure 7), indicating that the majority of NO_3^- leaching into the aquifer is derived from human or animal waste as opposed to agricultural fertilizers (Kendall 1998). Historical nitrate trends were also analyzed and do not correlate with a recent decline in piggery numbers (Figure 8), eliminating pigs as a likely cause of elevated groundwater NO_3^-. Further analysis of water quality data will continue to elucidate the sources and fates of excess nutrients in the region.

Measurement of Water Isotope δD and $\delta^{18}O$ Values

As of this writing, six months of water isotopes in precipitation data has been collected. At least one year of data is needed to begin drawing conclusions. However, the currently available data shows that this technique is producing promising results. Isotopic ratios of δD and $\delta^{18}O$ in precipitation are displaying variation based on season, in contrast to groundwater samples from wells (Figure 9). These results imply that this technique may prove to have utility in understanding the timeframes in which water recharges the aquifer and is intercepted by production wells.

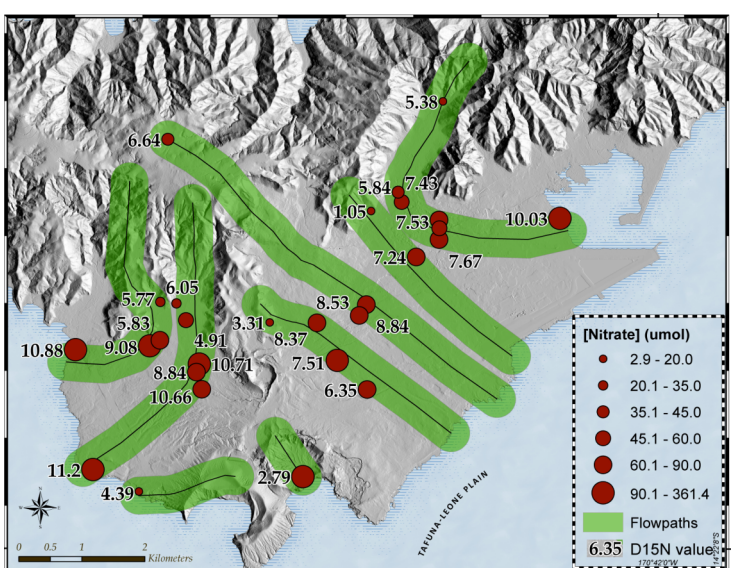


Figure 7. Values of $\delta^{15}N$ of NO_3^- in groundwater flowpaths in the Tafuna-Leone Plain region.

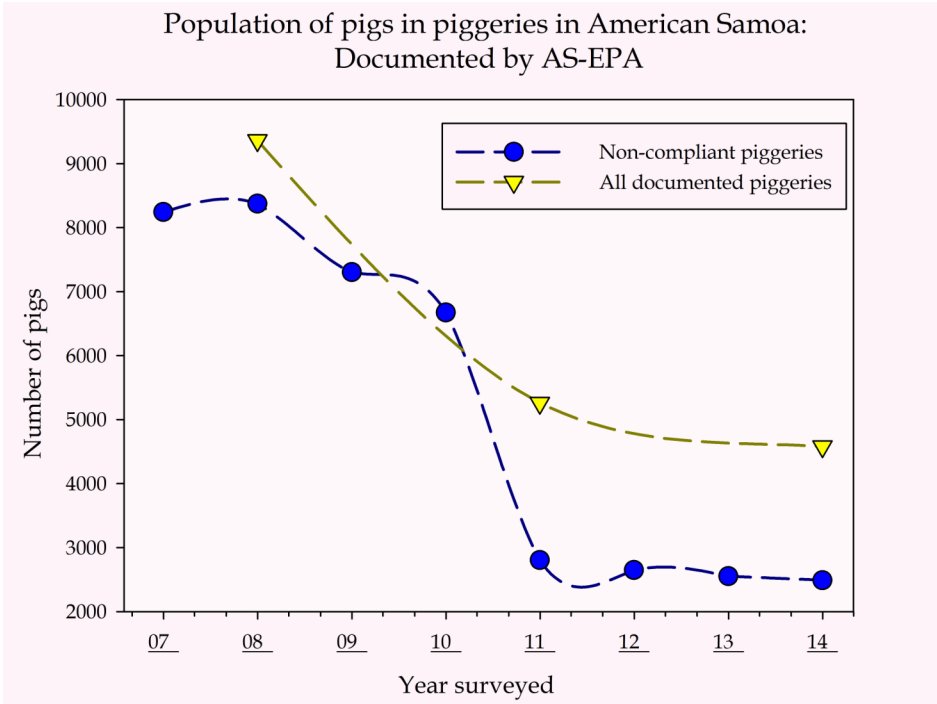
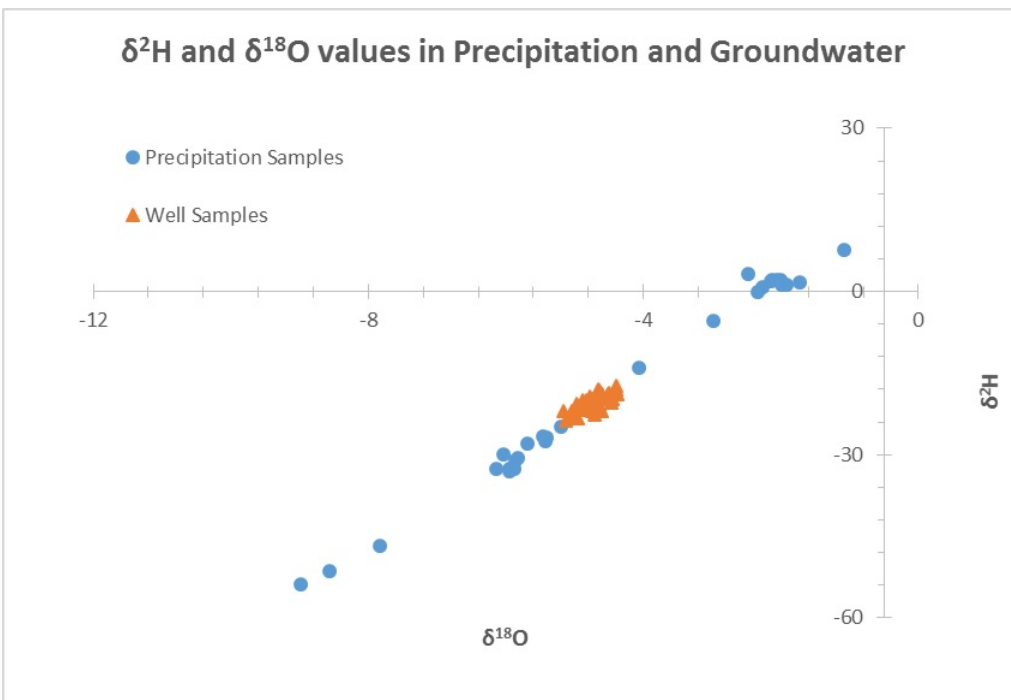


Figure 8. Populations of pigs in legal and illegal (non-compliant) piggeries on Tutuila since 2007. Data source ASEPA (2014).



Note: well samples cluster while precipitation samples vary along the meteoric water line.

Figure 9. Preliminary δD and $\delta^{18}O$ data from precipitation samples and well samples.

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Quantifying Groundwater Discharge from the Faga'alu Aquifer, American Samoa

Basic Information

Title:	Quantifying Groundwater Discharge from the Faga'alu Aquifer, American Samoa
Project Number:	2014AS429B
Start Date:	3/1/2014
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Solute Transport, Nitrate Contamination
Descriptors:	None
Principal Investigators:	Henrieta Dulaiova

Publications

There are no publications.

Problem and Research Objectives

Faga'alu Valley on Tutuila Island, American Samoa, has been designated as a priority watershed management area by the NOAA Coral Reef Conservation Program. While Faga'alu's surface water is on the AS EPA 3 03(d) list of impaired waters (CRCP 2013), at present, there is no information available regarding groundwater derived pollution in the valley. In its coral rich bay, near-shore ecosystem health is threatened by terrigenous sediments, nutrients, and other pollutants that are likely transported via stream and groundwater discharge (CWP 2012). The American Samoa Environmental Protection Agency's (ASEPA) coral reef monitoring program has determined that Faga'alu's benthic ecosystem is one of the most impacted on the island (Houk 2005).

This study strives to evaluate surface-water-groundwater interactions within Faga'alu Stream and to quantify groundwater to stream flux and submarine groundwater discharge rates into Faga'alu Bay. Since groundwater has been shown to be a potentially significant source of nutrients and other anthropogenic contaminants in similar environments (Johannes and Hearn 1985, Dulaiova et al. 2006, Burnett et al. 2007) a more complete understanding of groundwater derived contributions are needed to assess the degree of anthropogenic impact and nutrient loading to the coastal ecosystem. By examining multiple geochemical parameters and integrating ground/stream water flux rates with nutrient and isotopic tracer data we are currently working to quantify contaminant loading from different sources, and assess the degree of human impact on this fragile ecosystem.

Methodology

In summer 2014 a field campaign on Tutuila was completed. During this time samples and direct measurements were taken from the accessible length of Faga'alu Stream, from all observable coastal groundwater discharge sites, and throughout Faga'alu Bay.

Stream Sampling and Gauging Methods

Faga'alu Stream was sampled and/or gauged at nine locations throughout its lower reaches (Figure 1). Streamflow was measured using a Price-type Pygmy Current Meter and the velocity-area-method (Turnipseed and Sauer 2010) was used to calculate discharge. All stream samples were taken at baseflow conditions during a single 24 hour period. Samples were collected from the middle of the water column and filtered with a 0.45 µm hydrophilic polyethersulfone capsule filter. Temperature, salinity, pH and dissolved oxygen were measured in situ with a YSI multiparameter sonde (6600V2-4 model). Samples were collected in triple-rinsed acid cleaned 60 ml HDPE bottles and were immediately chilled for transport to storage facilities. Grab samples were analyzed the same day for dissolved radon gas concentrations and chilled samples were analyzed at University of Hawaii laboratories for inorganic nutrients, total dissolved C, N and P, major ions, δD & $\delta D^{18}O$ of water, $\delta^{15}N$ & $\delta D^{18}O$ of NO_3^- and $\delta^{13}C$ of inorganic carbon.

Coastal Groundwater Discharge Sampling Methods

A number of freshwater springs were identified along the coast at Faga'alu Bay. These were sampled and analyzed using the aforementioned stream sampling methods. Also three

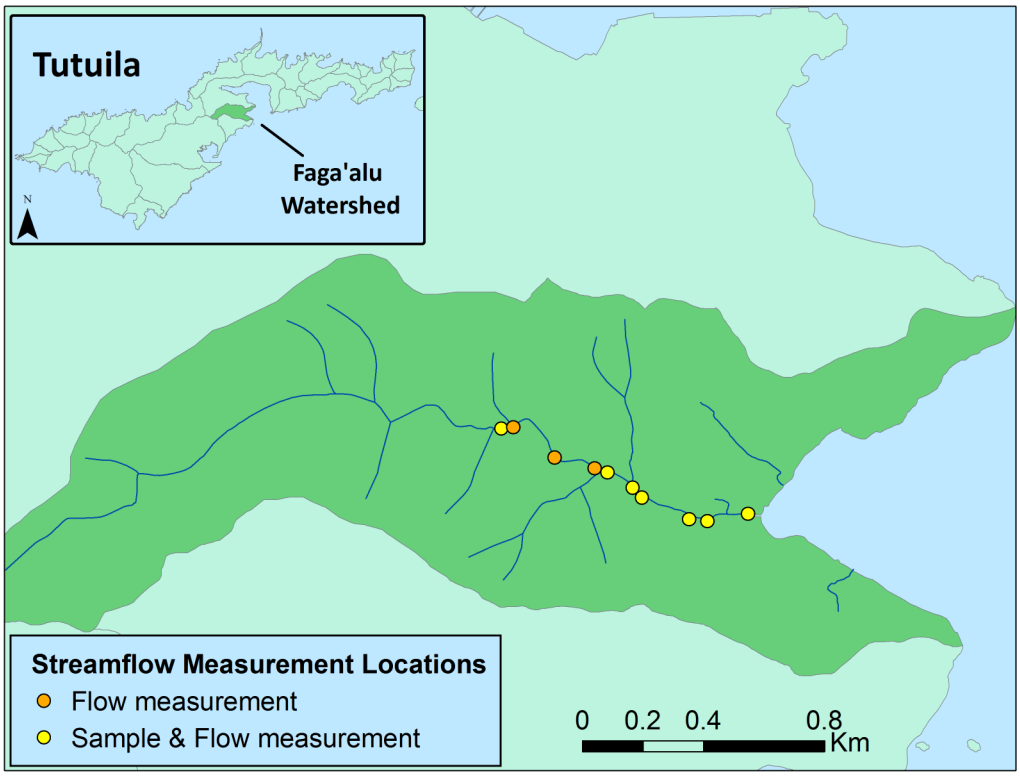


Figure 1. Stream gauging and sampling was performed in the lower reach of Faga'alu Stream. This reach encompassed the majority of human development within the valley.

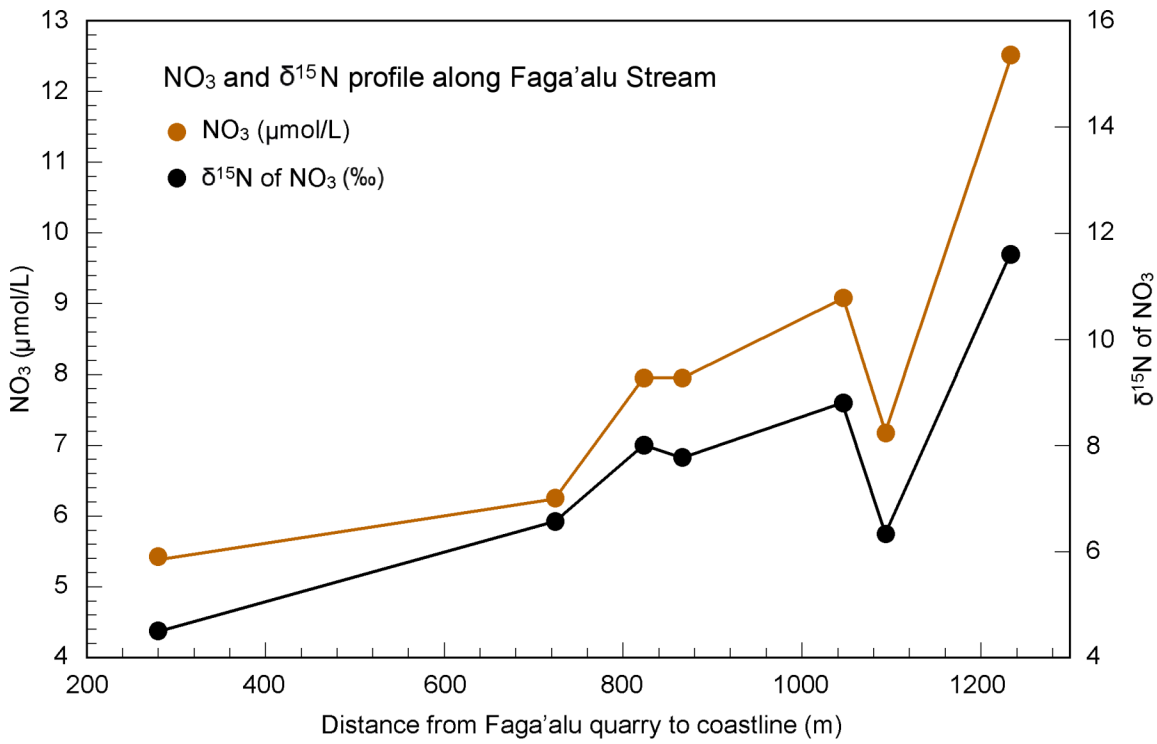
coastal groundwater discharge locations were selected for installation of two meter long PVC piezometers which were placed roughly 0.3 m below the water table. Piezometers were outfitted with conductivity, temperature, and depth (CTD) loggers for one week and water samples were taken during both high and low tide from one piezometer. There is a single production well in Faga'alu Valley and water samples from this well were also collected to be used as potential groundwater endmembers.

Coastal Water Sampling Methods

A coastal survey through the inner bay was conducted via boat during a low tide cycle. The craft was instrumented with a continuously logging YSI multiparameter sonde (6600V2-2 model) and a continuously logging dissolved radon gas detector (Durrage Rad7). In addition, depth profiles were conducted with a CTD logger every 5 minutes during the survey and coastal water samples were collected roughly every 10 minutes during the survey. Water samples were analyzed using the same procedures as the stream samples. Survey data is currently being analyzed with methods from Burnett and Dulaiova (2003) with updated gas-liquid equilibrium constraints based on equations in Schubert et al. (2012).

Time-series Deployment Methods

To quantify tidal variations in SGD a continuous stream of coastal water from a single location was pumped through on-shore instrumentation which included a YSI multiparameter sonde (6600V2-2 model) and a continuously logging dissolved radon gas detector. These



Note: The stream mouth is located 1,250 m from Faga'alu quarry.

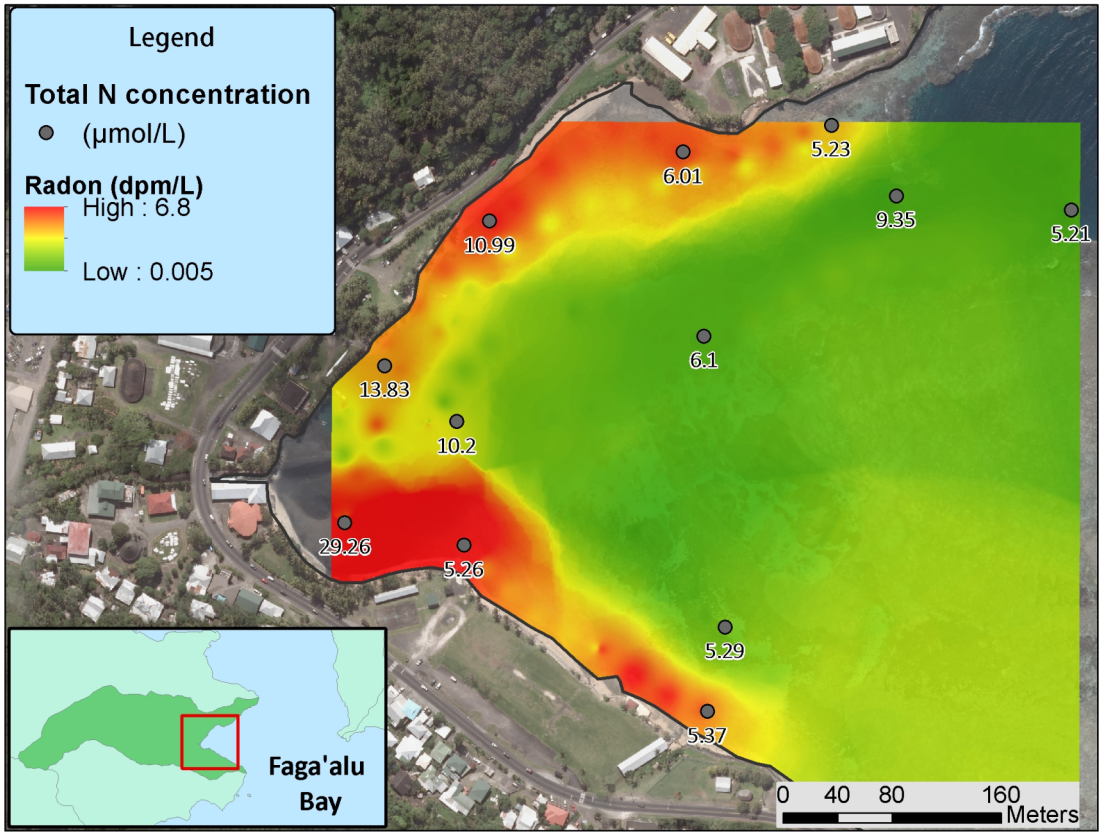
Figure 2. Nitrogen dynamics along Faga'alu Stream as it travels through the developed part of the watershed.

instruments recorded variations in salinity and radon gas concentrations over a 48-hour period consisting of multiple tidal cycles. Water samples were periodically taken from the apparatus and analyzed as mentioned above. Data is currently being analyzed

Principal Findings and Significance

Stream Water Quality and Nutrient Flux

Direct measurements of dissolved radon in Faga'alu Stream during baseflow conditions indicate a close connection between stream water and groundwater. The stream appears to be continuously fed with groundwater throughout its entire length, meaning dissolved constituents originating from the aquifer are discharged to the bay through not only coastal springs, but through the stream as well. Although the upper reaches of Faga'alu Stream are most likely gaining water via springs and seepage, gauging data indicates the lower reach is losing water to the aquifer over much of its length as it travels over the alluvial valley fill. Once the stream reaches an elevation nearing sea level, an increase in flow and a nearly four-fold increase in dissolved radon concentrations suggests a contribution to the stream from the basal groundwater lens. Streamflow throughout this lower reach is supplemented by small spring-fed tributaries which also bring radon and anthropogenic nutrients into the stream. Stream samples show an increasing trend of total nitrogen concentrations as well as $\delta^{15}N$ values as the stream travels through developed areas to the bay (Figure 2). This indicates inputs of nitrogen to the



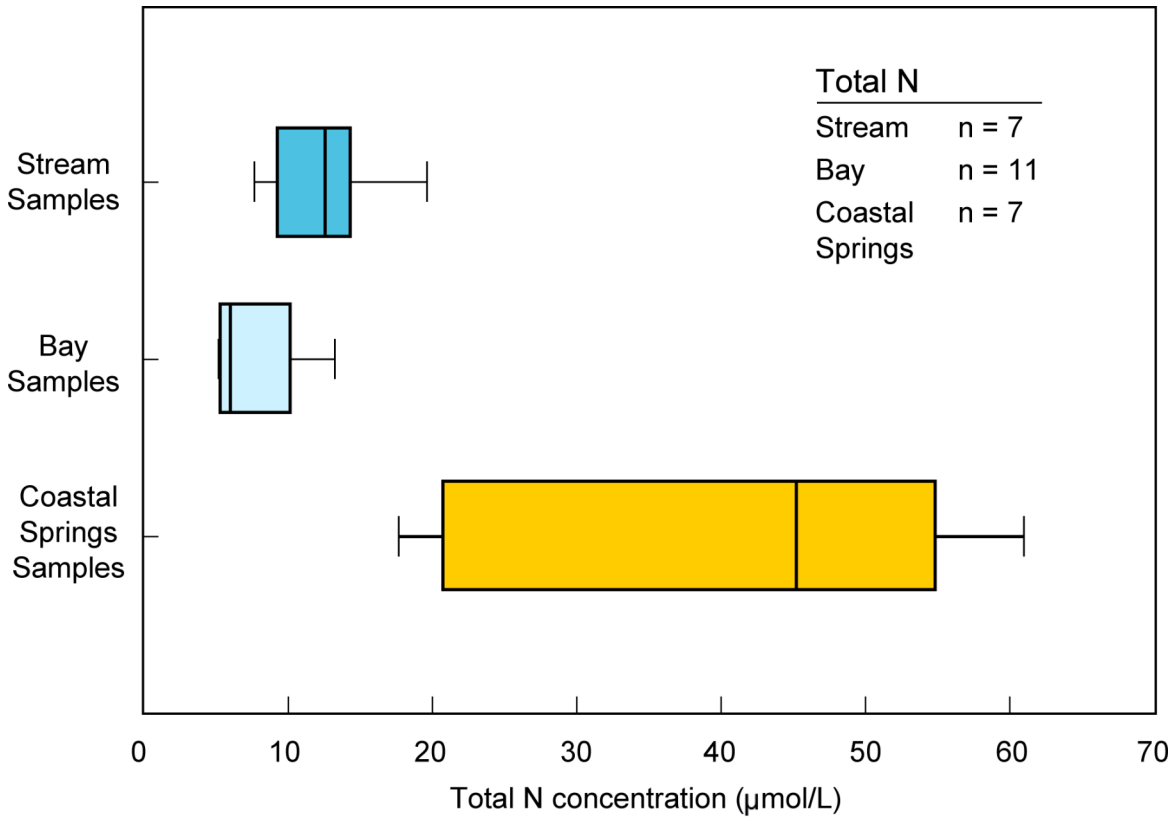
Note: Total N values are higher in the northern part of the bay, likely due to a counterclockwise current.

Figure 3: Results from coastal radon survey and water sampling. Dissolved radon concentrations are higher near the coast, indicating areas of groundwater discharge.

stream are most likely derived from human or animal waste products (Kendall and McDonnell 1998).

Coastal Water Quality and Groundwater Influence

Preliminary results based on measurement of coastal radon inventory, indicate a significant amount of groundwater is discharging into and influencing the chemistry of surface waters in Faga'alu Bay (Figure 3). In these coastal waters, levels of inorganic nitrogen also appear to be significantly higher than in ambient ocean water. Our study suggests that during low-flow conditions baseflow, as opposed to surface water contributions, acts as the primary source of nutrients in the stream. At present our analysis is continuing to focus on the delineation between the effects of stream derived inputs and those from groundwater, by looking at salinity measurements and radon concentrations. This coastal survey data and a recent sediment modeling study (Messina 2012) both indicate the presence of a persistent clockwise moving current in the bay that transports sediment, surface water, and any groundwater derived constituents from the south to the north side of the bay. Nutrient concentrations in coastal surface waters are roughly twice as high in the waters of the north side of the bay (Figure 3).



Note: Boxes represent 25th and 75th percentiles, whiskers represent 10th and 90th percentiles, bar indicates median value.

Figure 4. Box plot of total median N values in all stream samples.

Coastal Spring and Groundwater Nutrients

The four discrete coastal springs that were found were sampled multiple times over varying tidal conditions. The nearshore groundwater environment shows geochemical complexity and nutrient results vary widely depending on the timing of sampling (based on tidal stage) and the observed redox conditions in the water at the time. Although the speciation of nitrogen in coastal springs was highly dependent on localized redox conditions, the total nitrogen concentrations discharged to the bay from coastal springs were roughly 3–4 times higher than those observed in stream and coastal bay waters (Figure 4). Though we have yet to quantify groundwater flux rates into the bay, the low levels of observed nitrogen in stream waters and the only slightly lower concentrations of nitrogen found in coastal waters leads us to believe that groundwater nutrients are a significant controlling factor for the geochemistry of the bay. Further analysis will focus on understanding the unique aquifer chemistry and biogeochemical reactions that apply to the valley's groundwater.

Coastal spring and inland groundwater samples from Faga'alu are unique when compared to groundwater from other parts of the island. The valley has historically been subject to a higher degree of anthropogenic modification due to the presence of U.S. Navy operations. Many groundwater samples have unusually low dissolved oxygen concentrations, potentially indicating a buried source of organic carbon that may be related to construction fill historically used to create developable land in the valley.

Future Work

Objectives still to be completed include:

- Quantification of groundwater flux rates and plume geometry using methods similar to those in Peterson et al. (2009).
- Partitioning of stream water vs. groundwater as transport mechanisms for nutrients and other anthropogenic contaminants.
- Developing a better understanding of the biogeochemical reactions, (e.g., denitrification, sulfate reduction, etc.) which control groundwater chemistry and speciation of nutrients in the near shore environment.

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Building a polychaete species database for water management purposes in American Samoa

Basic Information

Title:	Building a polychaete species database for water management purposes in American Samoa
Project Number:	2014AS430B
Start Date:	3/1/2014
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Conservation, Invasive Species, Management and Planning
Descriptors:	None
Principal Investigators:	Julie Helen Bailey-Brock

Publications

There are no publications.

Problem and Research Objectives

The biodiversity of marine invertebrates from the American Samoa has been poorly characterized. Most of the efforts are concentrated on studying the coral reefs, which encompasses one of the most diverse assemblages of corals and fish of the south Pacific. The Indo-Pacific polychaete fauna is one of the most diverse worldwide, but only 30 species are recorded for the Samoan Islands and this is probably a result of few collecting efforts.

There is an extensive literature and interest on Palolo worms from Samoa with the first accounts dated from 1847 (Stair 1847). The swarming event of this species is celebrated and a cultural aspect of American Samoa as the worms are scooped up and eaten raw or cooked by the islanders. The interest on these worms has increased along the years and several papers describe its morphology (Woodworth 1903) and reproductive characteristics (Caspers 1964, 1984; Krämer 1897). More recently, Brown (2009) described additional notes on the spawning behavior of this species and Schulze (2006) shed some light on the phylogenetic relationships between the Pacific and Caribbean palolo worms.

Although palolo worms have been well-studied, other polychaete families that are known as being bioindicators of ecosystem health are poorly characterized in American Samoa. Some previous research concerning polychaetes from the Pacific Ocean are based on samples collected from sites around American Samoa and describe species that are endemic to that area. The first studies, with a taxonomic perspective were done by Treadwell (1921, 1922, 1926). Treadwell described 16 species collected from Pago Pago Harbor and among them 4 were endemic species to that area. Augener (1927) and Hartmann-Schröder (1965) increased this number to about 30 species.

Shallow water polychaete species were characterized qualitatively at several sites around American Samoa.The intent was to determine the polychaete species present in soft sediments, diverse algal assemblages and coral rubble to provide a polychaete species list that would be useful for future biomonitoring projects. There are few accounts of Samoan polychaetes and only about 20 species are recorded for those islands. The Indo-Pacific polychaete fauna is one of the most diverse worldwide and the low richness of species found in the Samoan Islands is probably due to scarce collecting efforts.

Methodology

Study Area

Fine and coarse sediment, coral rubble, and several species of algae and one species of sponge were hand collected around the surrounding areas of American Samoa with the intent of finding a diverse polychaete assemblage. Twenty sampling stations were selected around the island of Tutuila (Figure 1). All samples were collected on shallow waters up to 5 m deep. After collection, samples were sieved with seawater and all the polychaetes retained were sorted and preserved in 70% or 90% ethylic alcohol. Some individuals were observed and photographed while alive.

Polychaetes were sorted and identified using dissecting and compound microscopes. Species considered to be new to science will be fully described, illustrated, photographed under a Scanning Electron Microscope, and published in peer reviewed scientific journals. Samples were collected under a scientific research and collecting permit from the National

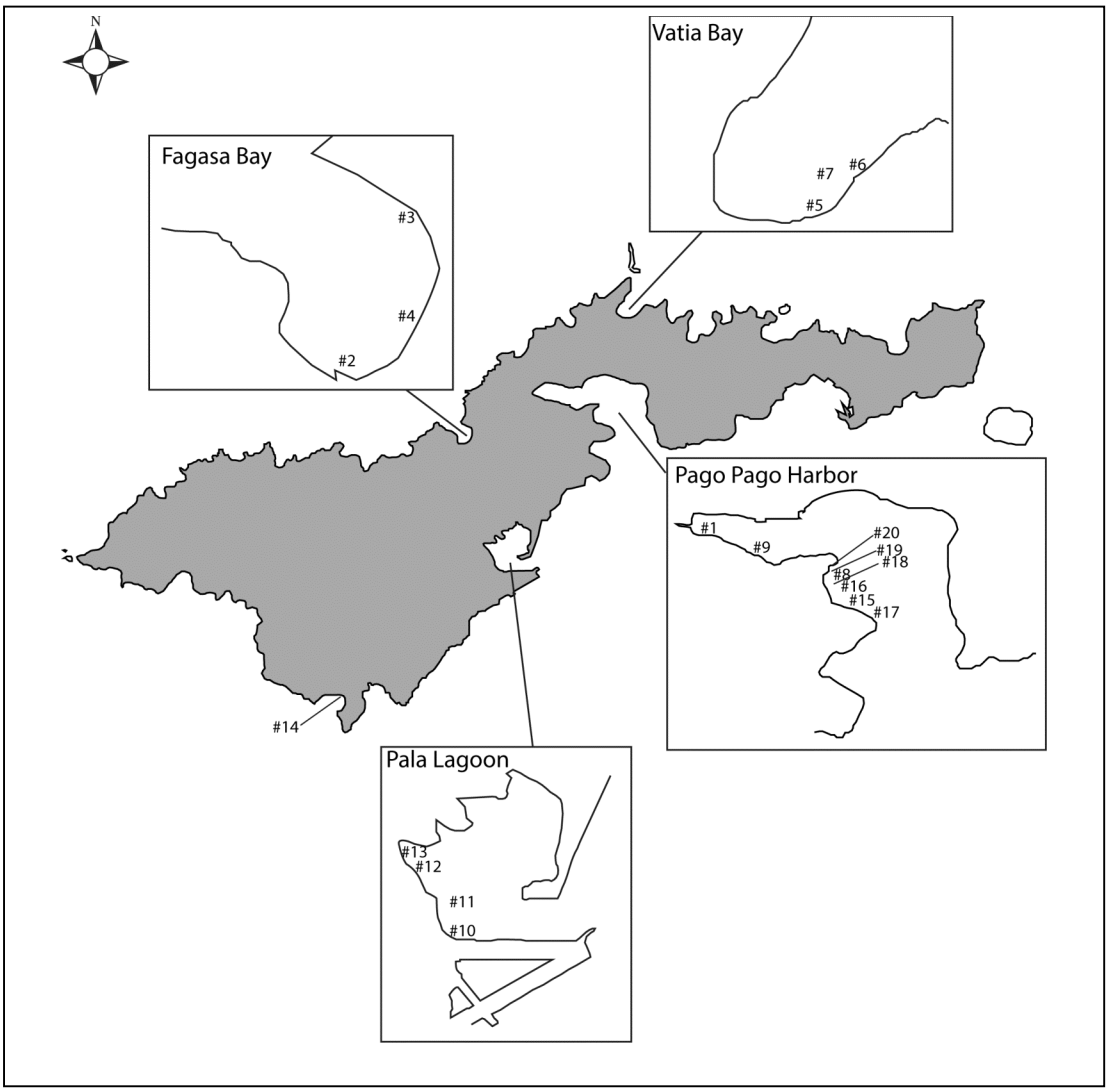

Figure 1. Map of Tutuila Island in American Samoa showing the sampling stations and including inset maps for Fagasa Bay, Vatia Bay, Pala Lagoon and Pago Pago Harbor.

Park of American Samoa (NPSA-2014-SCI-0007) and a scientific permit from the Department of Marine and Wildlife Resources from the American Samoa Government No. 2014/005.

Principal Findings and Significance

1. The shallow water polychaetes of American Samoa are very diverse with a total of 546 individuals collected in this study representing 26 families and more than 73 species.
2. At least one new species was collected from samples taken from this project and will be formally described and named.

3. Most of the species collected in this study (67 out of more than 73 species) represent new records for American Samoa and increase our knowledge of the polychaete worms present in that region of the southern Pacific Ocean.
4. The polychaete species from American Samoa appear to be significantly different from those of North Pacific including Hawaii and west of the United States coast, and more similar to the communities described for New Zealand and Australia.
5. The species *Hydroides elegans*, *Dipolydora socialis*, *Salmacina dysteri*, and *Sabellastarte spectabilis* are likely to have been transported to American Samoa and are accidental introductions. Impacts of these species have been reported in other regions of the Pacific Ocean.
6. The tube builder species *Mesochaetopterus minutus*, was collected in high abundance in Vatia Bay. This species is a gregarious worm that forms tufts of sand-covered tubes and play an important role in these assemblages by binding the sediments once suspended. It represents an ecologically important species for its rapid reproduction and propagation in disturbed sandy regions.
7. This was the first comprehensive study aimed to taxonomically describe and identify the polychaete worms around the island of Tutuila in American Samoa. All specimens will be deposited in the Bernice Pauahi Bishop Museum collection and made available for future researchers working on water quality and the effects on the benthic macrofauna in American Samoa.

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Long-term aspects of high-elevation rainfall and climate change, Oahu

Basic Information

Title:	Long-term aspects of high-elevation rainfall and climate change, Oahu
Project Number:	2011HI318B
Start Date:	3/1/2013
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Wetlands, Drought
Descriptors:	
Principal Investigators:	David Beilman

Publications

1. Schubert, Olivia, 2012, “Vegetation reconstruction of Ka‘au Crater through the Holocene,” MS Thesis, Department of Geography, College of Social Sciences, University of Hawaii at Manoa, Honolulu, HI.
2. Schubert, O.S., 2012, Changes in Vegetation and Environment over the Holocene, Ka‘au Crater, O‘ahu, Hawai‘i,, MA Thesis, Department of Geography, College of Social Sciences, University of Hawaii at Manoa, Honolulu, HI, 168 p. (in preparation, a manuscript from this research is planned for submission to Journal of Paleolimnology)
3. Schubert, O.S., 2012, Changes in Vegetation and Environment over the Holocene, Ka‘au Crater, O‘ahu, Hawai‘i,, MA Thesis, Department of Geography, College of Social Sciences, University of Hawaii at Manoa, Honolulu, HI, 168 p. (in preparation, a manuscript from this research is planned for submission to Journal of Paleolimnology)
4. Schubert, O., S. Pau, S. Hotchkiss, and D.W. Beilman, “Reconstruction of Holocene environmental change at a windward site in the Hawaiian Islands,” The Holocene. (in preparation)
5. Schubert, O.S. and D.W. Beilman, 2014, Poster PP11A-1317, American Geophysical Union Annual Fall Meeting, San Francisco, CA, USA.
6. Beilman, D.W., 2015, “Tropical Pacific climate and carbon dynamics reconstructed from Hawaii peat deposits,” Poster T02734, International Quaternary Association XIX Congress, Nagoya, Japan.

Problem and Research Objectives

The climate of the Hawaiian Islands, particularly rainfall, is notoriously dynamic across geographic space (Giambelluca et al. 2013) and has long been recognized to be strongly influenced over time by changes in the Pacific atmospheric circulation (Chu 1995). Timeframes of variation range from annual to decadal and longer, including ENSO- and PDO scale dynamics (Chu and Chen 2005). Mountain rain is the crucial input for groundwater recharge in Hawaii (Giambelluca 1993) and the ultimate source of much-demanded water resources for the City and County of Honolulu. Water resource planning into the future (years and decades) requires a long-term understanding of the patterns and drivers of climate variation and change.

Our study seeks to better understand the long-term patterns of rainfall and dry climate by reconstructing from organic sediments of Hawaiian mountain bogs the long-term ecohydrological changes at high-elevation sites on Oahu and other islands. We initially proposed two study sites, Kaau Crater in the southern Koolau Mountains of western Oahu and Mt. Kaala at the highest point of the Waianae Mountains of eastern Oahu. We have further expanded this network to include additional sites on Molokai and Hawaii Island.

Methodology

We use fossil pollen abundances reflecting changes in local vegetation over time and organic geochemistry including stable isotope analysis of bulk sediment and specific biomolecules. Fossil pollen work and geochemistry of Kaau Crater focused upon the last 8,000 years of well-dated sediments (Schubert 2012). Stable isotope geochemistry at all sites has focused on a comparison of contrasting conditions related to wetter windward locations and drier leeward locations. Sedimentary histories of n-alkanes derived from leaf waxes and lignin chemistry show wetness-driven changes in plant inputs and organic matter decomposition. Monitoring of microclimate conditions at some sites has been conducted to help determine important site-specific differences between sites (e.g., water table dynamics and the relationship between air and soil conditions), which are not available from archipelago-wide climate data products.

Principal Findings and Significance

Fossil Pollen

Pollen of approximately 34 different families of plants was discovered in Kaau Crater sediments, spanning the last 8,000 years. Of interest are changes in vegetation between 5,000 and 6,000 years ago, particularly in species in the palm family (Arecaceae) such as Pritchardia that suggest dramatic changes from very dry to very wet during this period. Pollen-reconstructed temperature anomalies suggest an overall cooling over the last 8,000 years, that follows decreasing summer solar irradiance during this time. Reconstructed precipitation anomalies show no overall trend, but dry-climate periods suggesting long-term rainfall decreases on the order of 500 mm (annual) particularly in the mid-Holocene around 6,000 years ago.

Organic Geochemistry

Vegetation changes evident in fossil pollen data are supported by our geochemistry results. Stable isotopes of carbon in bulk sediment from Kaau Crater show enriched δ13C values during dry-climate periods with more pollen from dry-loving plants. This windward site shows mutli-proxy evidence for changes in site wetness over time. Another line of geochemical evidence comes from CuO-extractable lignin (Ertel and Hedges 1984) in organic sediments from a mountain site on eastern Molokai. We identified different kinds of lignin in modern plant litter types to help build a library of chemical biomarkers and also made initial down-core measurements of lignin monomers at Pepeopae Bog on Molokai. Plants and organic sediments were found to be composed of about 1–4% extractable lignin in diverse assemblages. Dominant litter-producing plant types showed important differences in their lignin chemistry and the amount of extractable lignin as well as the types of lignin compounds varied considerably in the 9,000-year old sedimentary profile at Pepeopae that suggests that soil decomposition was more limited between 5,000 and 7,000 years ago than 4,000 years ago. Leaf wax geochemical measurements are ongoing.

Taken together, the long-term reconstruction of rainfall at mountain sites on Oahu and other islands shows that site wetness has varied considerably in the past, including periods of prolonged dry climate. Differences between sites and between island settings (wetter windward vs. drier leeward) has motivated a series of new ideas and hypotheses related to Pacific atmospheric circulation changes and their expression in complex rainfall in Hawaii. These data and activities supported by this grant have resulted in a proposal submitted to National Science Foundation in Fall 2014—it has been recommended for funding and research will begin July 2015.

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Giambelluca T.W., Q. Chen, A.G. Frazier, J.P. Price, P-S. Chen, J.K. Eishceid, and D.M. Delparte, 2013, "Online Rainfall Atlas of Hawaii," Bulletin of the American Meteorological Society, 94: 313–316, http://rainfall.geography.hawaii.edu

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Reshaping the Regulatory Framework for Hawaii Aquaculture - Water Quality Standards, Coastal Fishponds, and Shellfish Grounds

Basic Information

Title:	Reshaping the Regulatory Framework for Hawaii Aquaculture - Water Quality Standards, Coastal Fishponds, and Shellfish Grounds
Project Number:	2011HI323B
Start Date:	3/1/2013
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Law, Institutions, and Policy, Management and Planning
Descriptors:	
Principal Investigators:	Aly I El-Kadi

Publications

1. Penn, D., and M. Coleman, 2012, “Protective measures for shellfish areas—Exploring new water quality standards, watershed management approaches, and closure criteria for Hawaii’s coastal systems,” 15th International Conference on Shellfish Restoration, Groton, CT, Dec. 12–15.
2. There are no publications for 2013.
3. There are no publications for 2014.

FINAL REPORT

Reshaping the Regulatory Framework for Hawaii Aquaculture—Water Quality Standards, Coastal Fishponds, and Shellfish Grounds

May 2015

Aly I. El-Kadi

WRRC-2015-07

Project Number: 2011HI323B

Water Resources Research Center
University of Hawaii at Manoa
Honolulu, Hawaii

Problem and Research Objectives

Aquaculture is an important practice in Hawaii with roots in traditional practices as well as modern technology-based solutions. Hawaii's aquaculture production rose to $40 million in 2011 and the sector is continuing to expand; however, water quality regulations have not evolved in tandem to accommodate the needs of this growing industry. The goal of this project is to study and assess the regulatory framework related to the aquaculture industry through a broad-based collaborative effort that incorporates the considerable importance of the aquaculture industry while protecting and maintaining a healthy environment.

Research objectives that support the achievement of this goal are (1) identify potential water quality standards revisions; (2) document procedures and information needs for each type of revision; (3) analyze the revision process for a coastal fishpond; and (4) estimate the resources needed for wider-scale revisions.

Methodology

The regulatory framework for Hawaii aquaculture spans across federal, state, and county authorities. Through consultation with fishpond operators, shellfish growers, aquaculture scientists, and agency personnel, we are identifying and explaining the structure and mechanics of existing and potential measures for protecting and improving inland and coastal water quality, facilitating and expanding coastal fishpond operations, and establishing coastal shellfish grounds. Our efforts are based in technically based policy analyses, utilizing readily available regulatory information and scientific data through the University of Hawaii's WRRC's library as well as that of the University's Hawaii-specific scientific and regulatory history.

The study also involved tracking and evaluating legislative and regulatory initiatives and the outcomes of judicial proceedings that affect the options available for Hawaii producers and their watershed partners. Literature research on comparable water quality standards and shellfish sanitation programs across the U.S. and throughout the world was also carried out. Augmented by additional funding obtained through ongoing collaboration with Sea Grant investigators (Haws 2012), we are exploring options for a geospatial mapping component that is integrated with emerging Sea Grant research products such as the Hawaii Aquaculture Digital Atlas and utilizes newly available interactive viewers such as the Hawaii Aquaculture Marine Mapper (http://www.pifsc.noaa.gov/marinemapper).

Principal Findings and Significance

The project reviewed existing literature, followed promising developments, and consulted with a wide range of stakeholders involved in the aquaculture sector. The regulatory framework for Hawaii aquaculture has been evolving, albeit in an uncoordinated fashion. The project involved a number of meetings and discussions that were held with the scientific community, fishpond operators, and agency personnel to improve our understanding of the status, future prospects, and the growing research needs. The following are the identified revisions in the regulatory framework, which were detailed in the previous annual reports.

Potential revisions to the water quality standards that would support the advancement of Hawaii aquaculture include:

1. Changing the framework of water-body and marine bottom types and classes,
2. Establishing and assigning designated uses (uses to be protected) on a more site-specific basis,
3. Developing evaluative criteria that are explicitly tied to specific types, classes, uses, and sites, and
4. Developing and implementing biological monitoring and assessment methods that are directly linked with use attainment decisions.

Mechanisms for initiating such regulatory change are available for agencies, elected officials, and citizens through a variety of legislative and administrative processes, but will usually require agency cooperation to be successful.

The results of this study suggest that the State of Hawaii does not currently have sufficient resources to support the management of extensive near-shore shellfish growing grounds. However, the scenario is improving and significant accomplishments are pending that would greatly improve the regulatory framework for fishpond aquaculture. There is a great hope for the restoration of shellfish as a food supply in Hawaii based on (1) closed systems that use groundwater sources which more easily achieve the water quality requirements for growing area approval, and (2) cultivation in fishponds where public access can be limited and management efforts intensified.

Publications Cited in Synopsis

Haws, M., 2012, Expanding and diversifying near-shore mariculture in Hawaii and the U.S. Pacific Islands through resolution of regulatory, technical, and biological impediments, (national Sea Grant aquaculture research project awarded in 2012; D. Penn, key personnel), http://www.seagrant.noaa.gov/funding/2012_National_Sea_Grant_Aquaculture_Projects.pdf.

Island Director

Basic Information

Title:	Island Director
Project Number:	2011HI330B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Aly I El-Kadi, Philip Moravcik

Publication

1. There are no publications.

FINAL REPORT

Islands Director's / Workshop Conference

May 2015

Aly I. El-Kadi

Philip Moravcik

WRRC-2015-01

Project Number: 2011HI330B

Water Resources Research Center
University of Hawaii at Manoa
Honolulu, Hawaii

Island Director's Workshop / Conference

An effort was made to publish the conference proceedings for selected presentations made at the conference. However, a number of book publishers that were contacted declined, mostly due to the relatively narrow audience of specialized conference proceedings.

Overview

The issue of sustainability is especially critical for islands due to resource limitation and water vulnerability to contamination. The ever-increasing and competing demands include water supply to urban and rural communities, tourist facilities, industry, and farm animals. Additional non-consumptive uses include hydropower generation, navigation, and recreation. Further, alternative energy sources, such as bio-energy, have added more strain on water resources. Demands are multiplying due to population growth and urbanization. In some cases, water supplies are unable to deliver water on a 24-hour basis due to high leakage and sometimes wastage.

The issues related to the coordinated management of surface water and groundwater are of prime importance. Water resources are particularly sensitive to climate change due to islands' particular nature. Water scarcity and vulnerability to drought, flooding, and other natural disasters considerably increase as island size decreases. Major factors affecting water resources include physical island characteristics, such as size and topography, climate, and human impact. Climate change can lead to further degradation of water quality, which is already a major problem in many islands. Contamination originates from point and non-point sources. Pollution sources include discharges of untreated or partially treated wastewater and animal farms, inadequate solid waste disposal sites, agricultural chemicals, leakage of petroleum products and toxic chemicals, sediment erosion, and saltwater intrusion. The small size and steep slopes of catchments on high islands enable water and pollutants to move quickly to downstream areas. The highly permeable soils and shallow water tables on small coral islands facilitate the rapid migration of pollutants to the subsurface. The reversal of these negative impacts is difficult and time consuming. Pollution affects human health due to microbiological contamination and elevated chemical levels in water supplies. High turbidity and suspended solids are experienced by consumers after periods of heavy rainfall. The effectiveness of water supply intakes and treatment systems is compromised by high-suspended sediment loads, leading to higher costs of providing clean, safe water supplies. Sedimentation in water supply reservoirs and rivers lead to disturbances in upstream catchments. Finally, sediments, bacteria, and chemicals are negatively affecting riverine and coastal environments.

The conference presentations, addressing the issues outlined above, are grouped in sessions covering wastewater, flooding, climate, water supply and management, groundwater recharge, surface water and groundwater quality, water for energy, and submarine water discharge. Although most of the presentations are related to tropical islands, some method-oriented presentations were included that could be applied to these islands as well.

Evaluation of rapid QPCR method for enterococci with correlative assessment for molecular markers for sewage contamination in selected environmental water samples from Hawaii.

Basic Information

Title:	Evaluation of rapid QPCR method for enterococci with correlative assessment for molecular markers for sewage contamination in selected environmental water samples from Hawaii.
Project Number:	2012HI355B
Start Date:	3/1/2013
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Methods, Surface Water
Descriptors:	
Principal Investigators:	Marek Kirs

Publications

1. There are no publications.
2. There are no publications for 2014.

FINAL REPORT

Evaluation of Rapid qPCR Method for Enterococci with Correlative Assessment for Molecular Markers for Sewage Contamination in Selected Environmental Water Samples from Hawaii

May 2015

Marek Kirs
Roger S. Fujioka

WRRC-2015-02

Project Number: 2012HI355B

Water Resources Research Center
University of Hawaii at Manoa
Honolulu, Hawaii

Problem and Research Objectives

In a consent decree (NRDC 2008), USEPA agreed to address criticisms by 2012 of its current recreational water quality standards which are based on monitoring two traditional fecal indicator bacteria or FIB (*Escherichia coli*, enterococci). However, USEPA was not able to properly evaluate the methods and application of alternative fecal indicators such as *Clostridium perfringens*, coliphages, and *Bacteroides*. As a result, USEPA has proposed to continue to use the same recreational water quality standards, but has added the use of a rapid molecular method for enterococci to be implemented in 2013. The proposed USEPA recreational water quality criteria have raised two potential problems.

The current recreational water quality standards are based on the assumption that the source of FIB in recreational water is sewage and that the number of FIB correlates to the risk level for a sewage borne infection among swimmers. This was determined by epidemiological studies (Cabelli et al. 1982, Wade et al. 2006) when the source of contamination was known to be sewage. However, in epidemiological studies when the source of FIB is environmental rather than sewage, the risk of infection is not the same (NRDC 2008). Previous studies have shown that tropical environments favor the growth of FIB resulting in higher concentrations than found in temperature zones and the persistence of *E. coli* and enterococci in environmental sites such as soil, sand, sediments and on plants (Hardina and Fujioka 1991, Byappanahalli and Fujioka 2004). One problem in the application of a culture based or qPCR based method to monitor *E. coli* and enterococci is that these methods measure FIB from all sources and therefore, do not distinguish between sewage, animal, or environmental sources. The correlation of enterococci found by culture with a microbial source tracking (MST) assay, which can confirm the presence and the concentration of sewage or with *C. perfringens* would help determine the source of the enterococci. Previous studies have shown that monitoring for *C. perfringens* with FIB provides more reliable evidence for the presence of sewage than monitoring for *E. coli* or enterococci alone (Fujioka and Shizumura 1985, Fujioka et al. 1992).

Before the qPCR method can be used, the reliability of the new method when applied to environmental waters in Hawaii needs to be established. There are three factors that can affect the qPCR results. The first factor is the inhibition in the water samples to be assayed. There is evidence of more inhibition in water samples from tropical environments than those from temperate zones. In a recent study conducted at Boqueron Beach, Puerto Rico, 34% of the samples contained significant levels of PCR inhibitors (USEPA 2008). The second factor is whether there is a difference in the recovery of enterococci from an environmental source compared to a sewage source. The third factor relates to the ratio of dead to live enterococci in the water samples.

In summary, we will evaluate and establish the reliability of the qPCR base method for enterococci in water samples specific for the State of Hawaii. Results of the study will also enable the Hawaii Department of Health (HDOH) to decide if the USEPA's novel rapid test for enterococci is suitable for Hawaii and if the test should be incorporated into the water quality regulations. The project set the following objectives:

1) Evaluate the performance of the rapid qPCR test for enterococci (Method 1611; USEPA 2012) in Hawaiian waters in parallel with cultivation based assays and establish a protocol for its use.
2) Evaluate qPCR based MST tools for use in Hawaii and establish a protocol for their use.

Methodology

Monthly water samples were collected from 12 beaches on Oahu between 14 May 2013 and 08 April 2014 for a total of 151 samples (Figure 1). Beaches for this study were selected by the Clean Water Branch, HDOH. Additionally, a total of 117 water samples were collected from 9 sites in the Manoa watershed on a monthly basis between 21 May 2013 and 21 April 2014 (Figure 1). Triplicate raw sewage, pre-UV and effluent samples have been collected from the Sand Island Wastewater Treatment Plant. Triplicate raw sewage and effluent samples, as well as samples after primary and secondary treatment were collected at the Honouliuli Wastewater Treatment Plant. Fecal samples were collected from cats (*Felis catus)* (n = 10), rats (*Rattus rattus*) (n = 10), mongoose (*Herpestes auropunctatus*) (n = 10), and human volunteers (n = 10, ages 33 to 59, 1:1 female to male ratio) between 24 April 2013 and 24 June 2013.

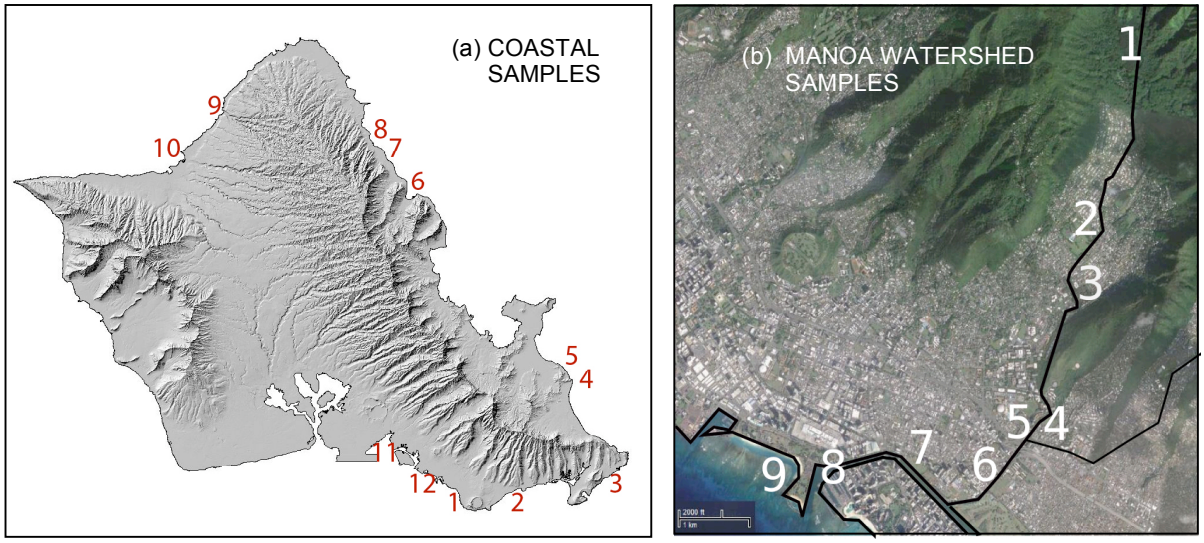

Figure 1. Sample locations on Oahu, Hawaii. (a) Coastal samples were collected at: 1 = San Souci Beach, 2 = Waialae-Kahala Beach, 3 = Sandy Beach Pt. No. 1, 4 = Kailua Beach Park, 5 = Kalama Beach, 6 = Kahana Bay, 7 = Punaluu Beach Park, 8 = Hauula Beach, 9 = Waimea Beach, 10 = Haleiwa Beach Park, 11 = Keehi Lagoon, and 12 = Ala Moana Beach middle section. (b) Samples from the Manoa watershed were collected at: 1 = 500 m upstream from Harold L. Lyon Arboretum, 2 = Manoa Elementary School, 3 = Manoa Marketplace, 4 = Koali Road before merger with Palolo Stream, 5 = Waialae Avenue after merger with Palolo Stream, 6 = Date Street bridge, 7 = Ala Wai Canal at McCully Street, 8 = Ala Wai Canal mouth at Waikiki Yacht Club, and 9 = Ala Moana Beach middle section.

For the survival and persistence study of indicator bacteria and MST markers, stream water was collected from Manoa Stream next to the University of Hawaii at Manoa campus (salinity = < 2, pH = 7.84) and seawater was collected from the middle section of Ala Moana Beach (salinity = 33.0, pH = 8.16) on 03 June 2013. Twelve liters of each water type were filter sterilized by passing the water through a 0.2 µm filter (Supor-200, Pall Corporation, Ann Arbor, MI). Twelve liters of each type of filtrate was spiked with 500 ml of raw sewage from the Sand

Island WWTP. The spiked filtrates were shaken twice for 30 seconds to evenly distribute the sewage and then divided equally among three sterile polypropylene containers (4 L final volumes). The containers were placed in the dark, kept at room temperature (22°C), and continuously agitated using magnetic stirrers. All six microcosms were tested for the survival of enterococci and *C. perfringens* by culture-based methods and for the persistence of molecular markers for enteroccoci; HBAC; and HPyV at days 0, 1, 3, 5, 8, 11, 15, 19, 24, 30, and 40. The sampling frequency was determined by the decay rates of the enterococci. Microbial decay rates were estimated based on the Chick-Watson first-order decay model (Chick 1908, Watson 1908) as follows: the geometric mean of concentrations in triplicate microcosms was calculated and the data normalized by dividing the mean of each time point by the mean of microcosm triplicates at the beginning of the experiment (C/Co). Normalized data were transformed with the natural logarithm (ln(C/Co)). Decay rates (k) and their 95% confidence intervals were calculated using a linear curve fit between ln(C/Co) and time. Data points below lower detection limits were excluded from rate calculation. The time to inactivate 90% of a given microbial population was calculated from the relationship T_{90} (days) = ln 10/k.

Each water sample was analyzed for (1) enterococci using membrane filtration and mEI media (Method 1600; USEPA 2002); (2) enterococci using Enterolert (MPN based method by IDEXX Laboratories; Westbrook, ME); (3) enterococci using a qPCR based rapid analysis protocol with polycarbonate filters (0.4 µm pore size) and 100 ml sample volumes (Method 1611; USEPA 2012) (Table 1); (4) *C. perfringens* using methodology specified in Bisson and Cabelli (1979), involving heatshock at 65°C for 15 minutes, followed by membrane filtration and incubation on mCP media under anaerobic conditions (GasPak™ EZ Anaerobe Pouch System (BD Diagnostics; Franklin Lakes, NJ) at 42°C for 24 hours; the phosphatase test, using ammonium hydroxide vapors, was used to confirm positive colonies; (5) human specific *Bacteroides* (HBAC) using the protocol specified in Haugland et al. (2010) (Table 1); and (6) human polyomaviruses (HPyV) using the protocol specified in McQuaig et al. (2009) (Table 1). To facilitate binding of virus particles to membrane filters (type GN-6, Pall Corporation), 300 ml sample portions were adjusted to pH 3.5 with 6N HCl prior to filtration.

Table 1. Primers and probes used in molecular tests.

Assay	Forward Primer	Reverse Primer	Probe	Reference
Method 1611	5'-GAGAAATTCC AAACGAACTTG	5'-CAGTGCTCTA CCTCCATCATT	5'-[FAM]-TGGTTCTCTCCGAA ATAGCTTTAGGGCTA-BHQ	Ludwig and Schleifer 2000
HBAC	5'-ATCATGAGTT CACATGTCCG	5'-CGTAGGAGTT TGGACCGTGT	5'-[FAM]-CTGAGAGGAA GGTCCCCCACATTGGA-BHQ	Haugland et al. 2010
HPyV	5'-AGTCTTTAGG GTCTTCTACCTTT	5'-GGTGCCAACC TATGGAACAG	5'-[FAM]-TCATCACTGG CAAACAT-MGBNFQ	McQuaig et al. 2009
Sketa	5'-GGTTTCCGCA GCTGGG	5'-CCGAGCCGTC CTGGTC	5'-[FAM]-AGTCGCAGGC GGCCACCGT-BHQ	Haugland et al. 2005

Concentrations of fecal coliforms and *E. coli* were determined only for the Manoa watershed samples using Colilert-18 test kits (IDEXX Laboratories; Westbrook, ME). F+ specific coliphages were determined in selected water samples collected from the Manoa watershed using the single agar overlay method with *E. coli Famp* as the host (Method 1602; USEPA 2001).

Fecal and sewage samples were analyzed for *C. perfringens*, HBAC, and HPyV just as with the water samples; and concentrations of enterococci were determined by Enterolert® only.

Briefly, 1 g wet weight of fecal matter was diluted in phosphate buffered dilution water and vigorously vortexed for 2 minutes. The fecal slurry was further serially diluted to 10^{-5}. The 10 ml sample portions were tested for enterococci and *C. perfringens* using cultivation based tests. DNA was extracted directly from 0.25 g of undiluted fecal matter for the molecular qPCR based tests (HBAC and HPyV). The limit of quantification was 1.3×10^3 gene copies /gram (gc/g) fecal matter for both molecular tests.

For the molecular tests, DNA was extracted using a PowerSoil DNA Extraction kit (MoBIO Laboratories Inc.). All qPCR runs included a 10-fold serially diluted 5-point standard in triplicate. A linearized plasmid containing a target specific insert was quantified on a fluorometer (Qubit 2.0 by Life Technologies Inc.) and used as a standard to derive MST marker quantities. All samples were analyzed in duplicate. Levels of PCR inhibitor were determined using the Sketa assay as in Haugland et al. (2005) (Table 1). Permits to import micro-organisms (controls), as well as an IRB permit to work with human subjects were obtained for this project by the PI.

Principal Findings and Significance

Presence and Concentration of Fecal Indicator Bacteria and MST Markers in Feces and Sewage, and their Decay Rates in the Environmental Waters of Hawaii

Fecal Indicator Bacteria

All human fecal samples were positive for enterococci, but only 7 out of 10 (70 %) contained *C. perfringens* spores. The average concentration of enterococci in human fecal samples was 4.07×10^4 MPN/g wet weight and ranged from 3.1×10^2 to 2.4×10^5 MPN/g wet weight (Table 2). The average concentration of enterococci in cat, mongoose, and rat fecal samples was 5.70×10^5, 1.36×10^6 and 7.07×10^6 MPN/g wet weight, respectively. The data collected so far indicate that animals such as the rat and mongoose, which are abundant in Hawaii urban and rural areas, may be an important source of enterococci in the environment.

Table 2. Fecal indicator bacteria and human marker concentrations in human subjects studied.

ID	Gender	Age at Date of Collection	Enterococci (MPN/g)	*C. perfringens* spores (CFU/g)	HBAC (gc/g)	HPyV (gc/g)
1	M	56	8.60×10^2	4.10×10^3	7.99×10^5	ND
2	M	49	1.20×10^4	10	173×10^6	ND
3	M	45	2.40×10^5	10	3.85×10^8	ND
4	F	33	2.40×10^4	9.60×10^2	6.63×10^4	ND
5	M	49	4.40×10^3	<10	4.61×10^6	ND
6	F	42	1.30×10^3	150	7.32×10^6	ND
7	F	43	4.10×10^3	<10	ND	ND
8	M	39	1.19×10^5	7.80×10^3	ND	ND
9	M	39	6.30×10^2	<10	2.97×10^7	ND
10	F	37	3.10×10^2	3.22×10^4	2.08×10^9	ND

Note: ND = not detected.

C. perfringens was isolated from 70% of humans tested (Table 2) which is comparable to an earlier study by Carman et al. (2008) where 63% of individuals (n = 43) were positive for *C. perfringens*. In another study conducted by Matsuda et al. (2009) in Japan, *C. perfringens* was detected in 48% of human samples (n = 40) tested. The concentration of *C. perfringens* spores in human feces varied from <10 to 3.2×10^4 CFU per g wet weight (Table 2). The study's average concentration of 4.52×10^3 CFU/g wet weight of feces was lower than concentrations reported in two earlier studies by Carman et al.(2008) and Matsuda et al. (2009) where average concentrations were 10^6 and 10^4 CFU/g wet weight of *C. perfringens*, respectively. These variations may be attributed to differences in methodology between studies (sampling protocols, media, anaerobic growth conditions, and other factors) as well as population differences. The concentrations of *C. perfringens* could not be reliably determined in cat, rat and mongoose feces and are not reported. Earlier studies have indicated that several animals, such as cats, pigs, dogs and others, can harbor high levels of *C. perfringens* (Cox et al. 2005, Vierheilig et al. 2013). Domestic and feral cats are known to harbor 7.9×10^5-6.9×10^7 CFU per gram of feces (wet weight) of *C. perfringens*, while concentrations were below detection limit in rat feces and feral pigs (Cox et al. 2005). Therefore, in theory, there are other sources—other than human beings—of *C. perfringens* that exist in Hawaii. In most cases, however, it is unlikely that this contribution is as significant as materials from large domesticated animals and human sewage. When deposited on land, *C. perfringens* is usually subjected to a natural filtration process through the soil matrix before the bacteria can reach the water.

Concentrations of enterococci in the three raw wastewater samples collected from the Sand Island and Honouliuli WWTP averaged 1.71×10^5 and 5.131×10^6 CFU/100 ml, respectively. Enterococci concentrations in the effluent were reduced to 3.70×10^3 and 4.55×10^3 CFU/100 ml, respectively, indicating at least two logs reduction of indicator bacteria in both WWTP. *C. perfringens* spores were more resistant to the treatment process. The concentration of *C. perfringens* spores in the three raw samples collected from the Sand Island and Honouliuli WWTP averaged 7.43×10^3 and 1.34×10^5 CFU/100 ml, respectively. The concentration of the spores was 4.37×10^2 and 2.33×10^3 CFU/100 ml, respectively, in the effluent in both treatment plants.

Microbial Source Tracking Markers

Human specific *Bacteroides* (HBAC) was detected in 8 out of 10 individual human fecal samples (80% sensitivity) and in all wastewater samples (100% sensitivity) (Table 2), hence the marker is highly prevalent among the population targeted by this assay. The marker was detected also in a single sample originating from cat and in three samples originating from mongoose. Therefore, the specificity of this marker based on our limited sample size was 87%. Concentrations of HBAC marker in human fecal samples were significantly higher when compared to samples exhibiting cross-reactivity. The concentration of HBAC varied in human fecal samples from $<1.3 \times 10^3$ to 2.08×10^9 gc/g (average 2.51×10^8 gc/g), while HBAC concentrations were $<1.3 \times 10^3$ in the single positive cat sample and $<1.61 \times 10^3$ gc/g in the cross-reactive mongoose samples. Average concentrations of HBAC marker decreased 79% over the wastewater treatment process (Table 3).

Human polyomavirus (HPyV) was not detected in any of the fecal samples tested, but HPyVwas detected in all the wastewater samples collected at the Sand Island WWTP. HPyV concentration varied from 1.34×10^4 to 3.81×10^4 in the raw influent, from 6.43×10^3 to 4.11×10^4 after primary treatment, and from 3.24×10^3 to 2.72×10^4 gc/100 ml after UV disinfection

(effluent sample). Average HPyV titers decreased 43% over the wastewater treatment process (Table 3).

Table 3. Average concentrations of indicator bacteria (enterococci and *C. perfringens*) and molecular markers (HBAC and HPyV) in the fecal and wastewater samples, Sand Island WWTP.

Sample Type	Sample Size	Enterococci MPN/g MPN/100 ml	*C. perfringens* CFU/g CFU/100 ml	HBAC gc/g gc/100 ml	HPyV gc/g gc/100 ml
Humans	10	1.49×10^5	5.23×10^3	2.51×10^8	ND
SIWWTP-raw[a]	3	1.71×10^5	7.43×10^3	2.65×10^7	2.34×10^4
SIWWTP-preUV[b]	3	3.00×10^4	1.53×10^3	9.39×10^6	2.45×10^4
SIWWTP-effluent[c]	3	3.70×10^3	4.37×10^2	5.48×10^6	1.34×10^4
Cats	10	3.00×10^5	7.5×10^5–6.9×10^7 [d]	Detected (9.56×10^2)	ND
Rats	10	7.07×10^6	<100[e]	ND	ND
Mongoose	10	2.45×10^6	NA	1.61×10^3	ND

Note: NA = data not available, ND = not detected; parenthesis are used to indicate concentrations that were below the limit of quantification.
[a] Raw influent.
[b] Sample collected after primary treatment, but before UV disinfection.
[c] Sample collected from the effluent after UV disinfection.
[d] Cox et al. (2005) and Vierheilig et al. (2013).
[e] Cox et al. (2005).

Decay of MST Markers

Based on the decay constants (k), the human-specific markers HBAC and HPyV decreased in concentration over time similarly to enterococci, both in freshwater and seawater (Figure 2). Concentrations of markers and enterococci tended to decrease slower in seawater than freshwater. This might have been an artifact caused by the experimental design because native grazers were removed from all experiments and grazers originating from sewage were likely better adjusted for the freshwater environment. The concentration of *C. perfringens* spores changed little over the study period, indicating that *C. perfringens* is a conservative sewage indicator that may remain viable for long periods of time after a contamination event when enterococci and human marker concentrations have receded.

Decay rate constants (k) and T_{90} of FIB and markers are shown in Table 4. Enterococci ($T_{90} = 9.4$), and HPyV ($T_{90} = 9.3$) presented very similar decay rates in freshwater, while HBAC ($T_{90} = 5.7$) had a faster decay rate in this water type, although not statistically significant (95% CI overlap with enterococci and HPyV). *C. perfringens* presented a significantly slower decay rate, with a T_{90} of approximately 128 days in freshwater.

Enterococci and human marker decay rates were always slower in seawater than freshwater, but not significantly (95% CI overlap in all cases). The *C. perfringens* decay rate appears to be faster in seawater ($T_{90} = 66.1$) than freshwater. This may have resulted from the short term change in concentration occurring between the days 7 and 12. HBAC ($T_{90} = 9.0$), HPyV ($T_{90} = 10.7$), and enterococci by culture ($T_{90} = 12.2$) showed similar decay rates in seawater. The *C. perfringens* decay rate in seawater was significantly slower than that of enterococci or the human specific markers.

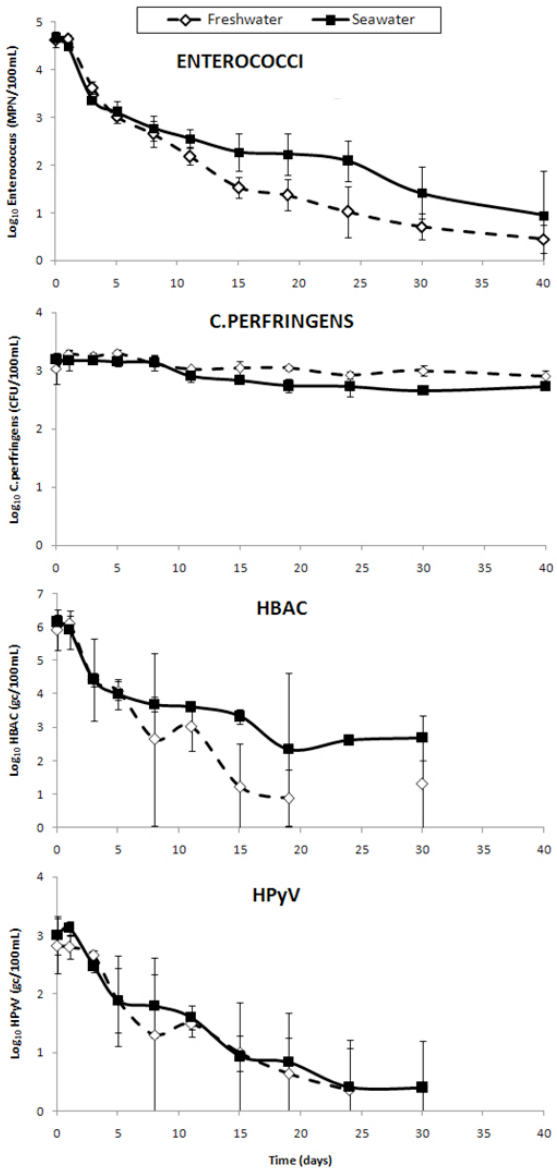

Figure 2. Decay of indicator bacteria in freshwater (collected from Manoa Stream) water and marine water (collected from Ala Moana Beach) water based on triplicate experiments. Water was filter sterilized then seeded with sewage at time 0. Triplicate microcosms were kept at room temperature in the dark.

Table 4. Decay rate constants (k) and respective 95% confidence intervals (CI) of indicator bacteria and molecular markers in freshwater and marine microcosms. T_{90} is estimated in days.

Indicator	Freshwater		Marine	
	Decay rate (k) [95% CI]	T_{90}	Decay rate (k) [95% CI]	T_{90}
Enterococci	-0.245 [-0.324 to -0.167]	-9.4	-0.189 [-0.249 to -0.129]	-12.2
C. perfringens	-0.018 [-0.030 to -0.006]	-127.9	-0.035 [-0.048 to -0.022]	-66.1
HBAC	-0.403 [-0.609 to -0.196]	-5.7	-0.255 [-0.377 to -0.132]	-9.0
HPyV	-0.247 [-0.313 to -0.182]	-9.3	-0.214 [-0.273 to -0.156]	-10.7

Rapid Methods and Beach Management

Overall there was a good agreement between the results derived by all three methods for enterococci (USEPA Method 1611 [rapid protocol], 1600 and Enterolert®) (Figure 3). R-squared values between the methods, varied from 0.62 to 0.82. There was also good agreement between beach management decisions based on methods compared pairwise (Table 5). When enterococci concentrations based on the Enterolert® and method 1600 were compared, both methods agreed on 68 samples, but disagreed on 12 samples (Table 5). Both methods would have resulted in 37 non-postings and 31 postings or violations of Hawaii STV. Nine samples would have been posted by Enterolert® but not by method 1600, while 3 samples would have been posted by method 1600 but not by Enterolert® (Table 5). Hence the beach management decision did not agree for 12 samples when these two methods were compared. When enterococci concentrations based on the Method 1611 and method 1600 were compared, both methods agreed on 67 samples, but disagreed on 13 samples (Table 5). When enterococci concentrations based on the Method 1611 and Enterolert® method were compared, both methods agreed on 62 samples, but disagreed on 28 samples (Table 5). It should be noted that 30 samples included in this analyses were collected from the brackish Ala Wai Canal (sites 6,7, and 8 (Figure 1)) as our one year study of coastal sites did not yield sufficient number of samples positive for enterococci by all three methods due to PCR interference and good water quality. While Ala Wai Canal is used for kayaking, it is not used for swimming and similar recreational activities involving full water-body contact.

Table 5. The comparison between beach management decisions derived by the three different methods. USEPA method 1600 utilizes mEI media and membrane filtration method, while Enterolert® method utilizes Defined Subtracted Methodology®. USEPA method 1611 is a novel rapid qPCR based test.

Method		Enterolert®		Method		Method 1600		Method		Enterolert®	
		No post	Post			No post	Post			No post	Post
1600	No post	37	9	1611	No post	42	7	1611	No post	35	14
	Post	3	31		Post	6	25		Post	4	27

Note: Number of samples that agreed by the methods compared are indicated in green, hence identical beach management decisions (post or not post beach warning notification) would have been made for 68 samples when analyzed by Enterolert® or method 1600; for 67 samples when analyzed by method 1600 or method 1611; and for 62 samples when analyzed by Enterolert® or method 1611.

According to the recently released guidelines by the EPA (USEPA 2014), an alternative method such as rapid qPCR based method for enterococci (Method 1611) can be used when the R-squared value of the two methods compared (alternative and EPA indicator method) exceeds 0.6. In this study the R-squared value exceeded 0.6, when the method 1611 was compared to either EPA cultivation based methods (1600 and Enterolert®). However 69.3% of coastal samples (n = 127) were strongly inhibited and could not be analyzed by the rapid molecular method. When 88 inhibited samples were diluted 1:10 in dilution buffer, only 3 of the compromised samples improved and could be analyzed. All these samples were not inhibited for more than a single PCR cycle when extracted using a commercial kit, linking the issue to the rapid extraction protocol which while effective for DNA recovery, does not include a column based purification step. Furthermore, 39 samples (analyzed in parallel) collected from freshwater

to brackish water environments (3 sites in Ala Wai Canal) were not inhibited. The exception was a single sample collected at Ala Wai mouth (site 8). This suggests that the inhibition is associated with Hawaii coastal water but not with freshwater environments.

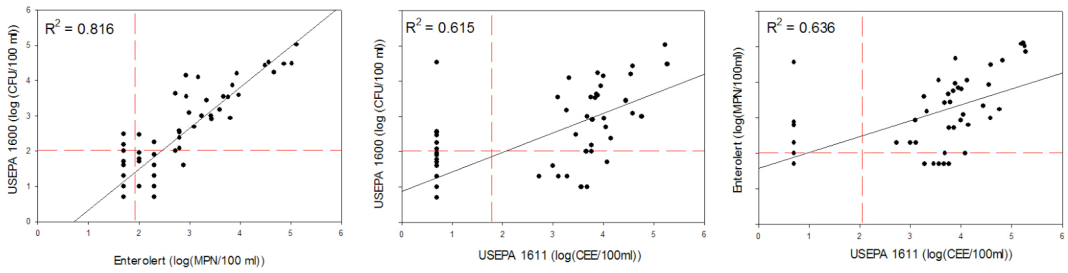

Figure 3. The comparison between enterococci concentrations derived by three different methods. USEPA method 1600 utilizes mEI media and membrane filtration method, while the Enterolert® method utilizes a Defined Substrate Methodology®. USEPA Method 1611 is a novel rapid qPCR based test. Red dashed lines indicate single sample maxima (104 CFU), which was utilized during the study period for beach notifications by HDOH.

Application of Microbial Source Tracking Markers to Identify Contamination Sources

Coastal waters

In general our samples indicated a good water quality in Hawaii coastal waters during the study (05/21/2013–04/21/2014). Enterococci concentrations varied from <10 to 389 MPN/100 ml (average 24 MPN/100 ml) and *C. perfringens* concentrations varied from <1 to 96 CFU/100 ml (average 3 CFU/100 ml) (Table 6).

Table 6. Indicator bacteria (enterococci and *C. perfringens*) concentrations in the Hawaii coastal water samples collected in 2013 and 2014.

Site	Number of Samples	Enterococci GM (CFU/100 ml)	*C. perfringens* GM (CFU/100 ml)	Samples Exceeding HI STV for Enterococci	Samples Exceeding HI STV for Enterococci and *C. perfringens*
1	13	8.9	0.5	0	0
2	13	6.7	0.5	0	0
3	13	6.0	0.7	0	0
4	13	7.7	0.8	0	0
5	13	6.4	0.7	0	0
6	13	43.9	1.5	2 (15.3%)	0
7	13	24.5	0.7	0	0
8	13	6.4	0.7	0	0
9	8	10.0	0.5	0	0
10	13	8.1	0.9	0	0
11	13	17.6	5.3	1 (7.6%)	1 (7.6%)
12	13	7.3	0.6	0	0

Note: GM = geometric meat, STV = statistical threshold value; % = sample positive ÷ total no. of samples.

In accordance with the new recreational water quality criteria, Hawaii utilizes an enterococci based statistical threshold value (STV) for beach notification purposes in parallel with a *C. perfringens* based standard. Currently freshwater and marine beaches in Hawaii are posted with warning signs when the STV exceeds 130 CFU/100 ml of enterococci and the *C. perfringens* concentration exceeds 50 CFU/100 ml. The HI STV for enterococci was exceed in 3 out of 151 samples collected (2% samples) at 12 beaches: twice at Kahana Bay Beach and once at Keehi Lagoon. Only this single sample from Keehi Lagoon also exceeded the *C. perfringens* standard. We did not find any of the human specific markers in the samples collected from Kahana Bay Beach indicating that the elevated concentrations of enterococci were likely from environmental sources (such as soil, sediments, leaf debris) and/or animal sources. In contrast, 5 out of 13 samples (38%) collected at Keehi Lagoon were positive for human *Bacteroides* marker indicating possible sewage related impairment in the lagoon. No human polyomaviruses were detected in the coastal samples. Our MST marker data support utilization of *C. perfringens* as sewage specific indicator in Hawaii.

Manoa Watershed

The 117 samples were collected in the Manoa watershed from 21 May 2013 to 21 April 2014. Based on those samples, microbial concentrations varied vastly in the watershed. Total coliform concentrations varied from 52 to >241,960 MPN/100 ml (average (26,170 MPN/100 ml), *E. coli* concentrations varied from <10 to >241,960 MPN/100 ml (average 3,295 MPN/100 ml), enterococci concentrations varied from <10 to >241,960 MPN/100 ml (average 2,263 MPN/100 ml), *C. perfringens* spore concentrations varied from <1 to 820 CFU/100 ml (average 60 CFU/100 ml), heterotrophic bacteria concentrations varied from <2,000 to >7,388,000 MPN/100 ml, and coliphage concentrations varied from <10 to 500 PFU. Without exception, the highest concentrations of the microbial parameters were found at sites 2 to 6 which are located in the urbanized section of Manoa Stream (Figure 4).

Enterococci concentrations were elevated in all the samples collected from Manoa Stream, and exceeded Hawaii's STV. Also *C. perfringens* concentrations exceeded the 50 CFU/100 ml limit (Figure 4) at all sites except site 1, which is located upstream from Lyons Arboretum in non human habitated rainforest (Figure 1). Indicator bacteria concentrations decreased at tidally influenced sites 6 to 9.

The human polyomavirus and human *Bacteroides* markers were identified at sites 2–9. The human *Bacteroides* marker was also identified at site 1 (non human habitated rainforest site), but only on two occasions (Table 7). Furthermore, the human *Bacteroides* marker concentrations were at least 2 logs lower at site 1 than at sites in the urbanized area (Figure 4). It may be that at site 1 the signal originated from a cross-reactivity discussed in an earlier section. It is unlikely that human sewage is present at that site. This conclusion is also supported by the *C. perfringens* concentrations at this site (ranging from <1 to 40, average 11 CFU/100 ml) which never reached the 50 CFU/100 ml that is typically associated with sewage impacted freshwater systems. Nevertheless, our source specific markers combined with traditional microbial data strongly suggest sewage based impairment in the urbanized section of the watershed (sites 2–8). The sewage signal appears diluted in the tidally influenced sites (sites 6–9).

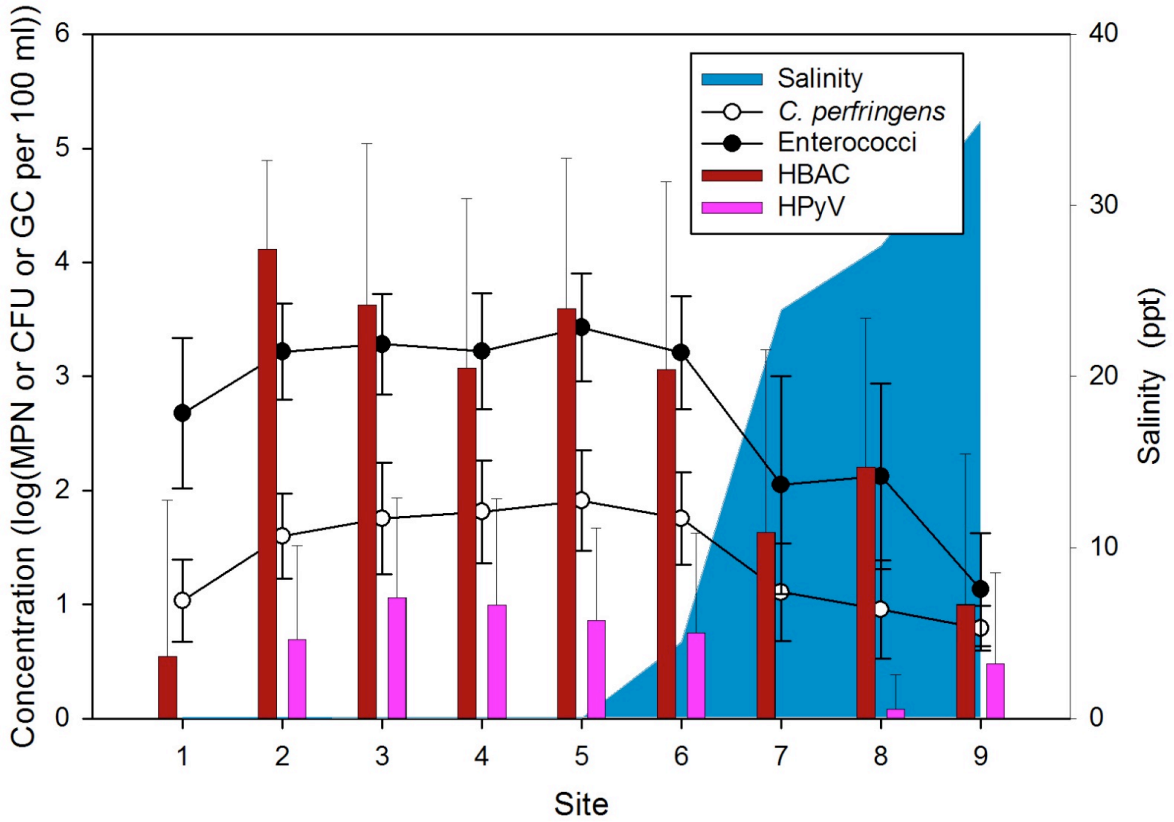

Figure 4. Distribution of fecal indicator bacteria and human specific markers in the Manoa watershed (05/21/2013 and 04/21/2014, n = 117).

Table 7. The number and percentage of positives for the human polyomavirus and the human *Bacteroides* marker at each site in the Manoa watershed. (n = 13 at each site.)

Site	1	2	3	4	5	6	7	8	9
Bacteroides	2 (15%)	13 (100%)	12 (92%)	11 (85%)	12 (92%)	11 (85%)	9 (69%)	10 (77%)	5 (38%)
Polyomavirus	0 (0%)	5 (38%)	8 (62%)	8 (62%)	7 (54%)	6 (46%)	0 (0%)	1 (8%)	3 (23%)

Note: Site 1 = non human habitated rainforest, sites 2–8 = urbanized area, and sites 6–9 = tidally influenced.

Conclusions

1. While rapid methods are needed and promising, in its current form method 1611 cannot be used in Hawaii due to the PCR inhibitors. This inhibition results from the rapid DNA extraction protocol and is associated with coastal waters but not with inland waters of Hawaii.

2. The 151 coastal samples indicated good water quality of our coastal waters, but 117 samples collected from the Manoa watershed indicates possible sewage related impairment in the urbanized section of the watershed.
3. Both human *Bacteroides* and human polyomavirus markers, are well suited for microbial source tracking purposes in Hawaii.
4. Distribution of source specific markers and *C. perfringens* in the coastal and watershed samples studied indicates that *C. perfringens* is a reliable sewage indicator and justifies its use as a water quality standard in Hawaii.

In summary our result indicate that PCR inhibitors associated with samples collected in Hawaii coastal waters needs to be addressed before rapid tests can be used for beach notification purposes in Hawaii. Based on the microbial source tracking analyses, our samples contained enterococci from human and environmental sources. Cultivation based and molecular tests for enterococci provided comparable results as indicated by the reported R-squares (>0.6) and beach management decisions. The good correlation between molecular and cultivation based measurements of enterococci in Hawaii coastal waters indicates that the ratio of dead to live cells of did not interfere with the concentration estimates of enterococci and was likely a minor factor in Hawaii coastal waters.

Project Output

As an extension from this project, we have submitted a grant proposal "*Rapid Response: Application of a qPCR based test for enterococci as a rapid beach management tool in Hawaii*" to the Hawaii Sea Grant. Our pre-proposal passed initial screening and we were asked to submit a full proposal, which was submitted 14 April 2015 ($59,968 + graduate assistant support, pending). Also, we gained interest from the Clean Water Branch at HDOH and initiated a new microbial source-tracking project at the Kahaluu watershed. We have received $35,000 funding for this project from HDOH.

This project was presented at the Molecular Training Worskshop (November 2014) at the Institute of Marine Sciences (IMS; University of North Carolina at Chapel Hill) as well as at the Ocean Science Meeting 2014 organized by Association for the Sciences of Limnology and Oceanography (ASLO), The Oceanography Society (TOS), and the American Geophysical Union, and at the WRRC seminar on 16 April 2015 (a pdf and video are available online at the WRRC website). Results from this project have also been presented at the Stem Pre-Academy workshop to Hawaiian teachers and in the Marine Microbiology class (MICR 401) to University of Hawaii students.

So far, three manuscripts from this project have been generated. One manuscript is currently being externally reviewed for submission to a journal, while the other two are in the preparation stage.

The ability to effectively monitor water quality and to determine the source of a contamination event is important for public health. To possibly establish a new protocol, this study evaluated the rapid qPCR based method for enterococci (USEPA 1611) as well as two microbial source tracking markers on the coastal, freshwater, and sewage samples collected in Hawaiian waters. Although there is a need to improve the rapid qPCR based method (USEPA 1611) before it can be utilized in Hawaii, two human specific markers can be used to identify human contamination sources immediately.

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Promoting Water Sustainability Literacy

Basic Information

Title:	Promoting Water Sustainability Literacy
Project Number:	2012HI356B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	Education, Water Use, Conservation
Descriptors:	
Principal Investigators:	John Cusick, David C. Penn

Publication

1. There are no publications.

Methodology

Students were involved in planning events, including the University of Hawaii Earth Day 2015 and are currently seeking approval for a mural depicting sustainability themes, including water, watersheds, and biological and cultural diversity.

Significance

Students in the Fall 2014 UHM Environmental Studies Practicum taught by WRRC faculty member John Cusick completed several internship and campus action projects that supported project objectives. Building campus water sustainability literacy nurtured greater capacity for critical thinking, problem solving, individual responsibility, and contributed to achieving the UHM Strategic Plan goal of developing a sustainability ethic on campus. In support of water literacy project efforts, the UHM Ecology Club co-sponsored 2015 Earth Week festivities on campus on April 22, 2015 where dozens of informational booths were set up by campus and community organizations. Several hundred people attended the event.

Bioaccumulation and Biotransformation of Arsenic by Marine Algae in Hawaii

Basic Information

Title:	Bioaccumulation and Biotransformation of Arsenic by Marine Algae in Hawaii
Project Number:	2012HI389B
Start Date:	3/1/2013
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Surface Water, Toxic Substances
Descriptors:	
Principal Investigators:	Philip Moravcik

Publication

1. There are no publications.

Problem and Research Objectives

For several decades arsenical compounds were used in the Hawaiian Islands as pesticides in the sugar industry. Although their use was discontinued in the 1940s, much arsenic remains in the soil of former sugarcane fields and has been continually transported with water, mostly bound to soil particles, into the coastal waters of Hawaii.

Seaweeds, or *limu* (in Hawaiian) are an important part of Hawaiian cuisine and several species are highly prized by local cooks. It is common practice in Hawaii to gather these algae along shorelines where they wash up. Arsenic is toxic in several of its forms and therefore there are justifiable concerns about the safety of consuming algae from waters subject to arsenic contamination. The validity of this concern is reinforced by the fact that some seaweeds have been shown to concentrate arsenic (Diaz et al. 2011, Granchinho et al. 2001).

Research conducted on behalf of The Nature Conservancy in Hawaii has revealed that seaweed collected at certain shoreline areas in the islands contains relatively high concentrations of arsenic. Algae can transform arsenic between a number of states, metabolizing the arsenate and arsenite to less toxic methylated forms (Granchinho et al. 2001). This has implications for the level of risk posed by consumption of algae and its use as a soil amendment. The objective of this study is to measure the arsenic content in algae collected from nearshore waters around the Island of Oahu and to characterize the speciation of any arsenic to see in what form it is occuring.

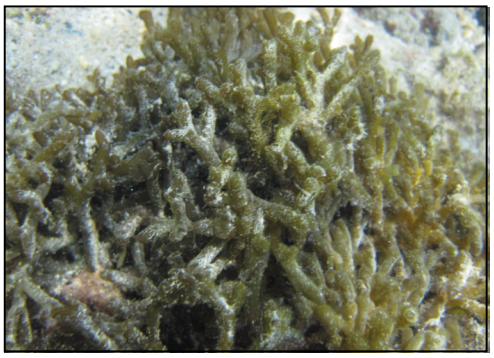


Figure 1: *Gracilaria salicornia*.

Methodology

We collected preliminary samples of an alga identified as *Gracilaria salicornia* (Figure 1) from the shore at Waikiki Beach in Honolulu (21.265253° N, -157.822206° W, Figure 2). *Gracilaria salicornia* is one of the most successful invasive algae on reef flats in Hawaii. It is related to, and competitive with, the popular edible alga *Gracilaria coronipifolia.* The collected samples were freeze-dried the day after sampling and the material sent to our collaborating laboratory at the Illinois Sustainable Technology Center (ISTC), at the University of Illinois at Urbana-Champaign, for analysis. Preliminary analyses conducted at the lab were not able to fully speciate the total arsenic found in the sample. Subsequent work by ISTC Senior Analytical Chemist John W. Scott and his team resulted in a fuller accounting of the different species that made up the total arsenic found in the sample.

Figure 2: Sample collection site.

Sample Preparation

The sample was homogenized with the aid of a gyromill and was milled to a fine powder (Figure 3).

Figure 3: Milled *G. salicornia* sample.

Total Arsenic Digestion

To prepare the sample for total arsenic analysis by inductively coupled plasma mass spectrometry (ICP-MS), a microwave digestion procedure was employed. A quarter-gram of homogenized sample was digested in a CEM microwave digestion system for 40 minutes, with the addition of 10 ml nitric acid and 1 ml hydrogen peroxide. After cooling, the sample was transferred to a centrifuge tube and diluted to a final volume of 50 ml. A reagent blank, an arsenic standard matrix spike, and a certified dogfish muscle tissue sample were processed in parallel to the sample to verify sample preparations. A matrix effect was observed for these samples; therefore, a second microwave procedure was performed (see Total Arsenic Analysis section). The second microwave digestion employed was identical to the first with the exception that one tenth of a gram of homogenized sample was processed. In addition, the trifluoroacetic acid (TFA) extracted solids (0.078 g) for one algae sample were digested in this batch as well.

Extraction Methods

To prepare the algae sample for arsenic speciation analysis by liquid chromatography-inductively coupled plasma mass spectrometry (LC-ICP-MS), solid-liquid extractions were performed. A quarter-gram of homogenized sample was treated with 5.0 ml TFA at 65°C for two hours. Afterwards, the sample was shaken with a laboratory mixer for 15 minutes. The TFA was collected and the procedure was repeated two more times while the TFA phases were pooled. The pooled fraction was then centrifuged for 20 minutes at 2,000 RPM and the final TFA fraction was decanted into a drying tube. The TFA was then removed under a gentle stream of nitrogen, and the residue was reconstituted in 10 ml of 0.2% hydrochloric acid. A reagent blank, an inorganic arsenic matrix spike, and a certified dogfish muscle sample were processed in parallel to verify sample extraction.

Total arsenic analysis of the TFA extracts indicated that the extraction of arsenic was incomplete; therefore, a second extraction of one of the TFA extracted solids was performed. The second extraction was identical to that of the first with the exception that a methanol-water (3:1) extraction fluid was utilized and the extraction was performed at 55°C. A reagent blank, an inorganic arsenic matrix spike, and a certified dogfish muscle sample were processed in parallel to verify sample extraction.

Total Arsenic Analysis

Total arsenic analysis was performed with a VG Elemental PQ Excel ICP-MS. Yttrium was utilized as an internal standard and the instrument was calibrated daily with reference materials procured from SPEX Certiprep. Verification of instrument calibration was achieved with preparations and analysis of two independent reference materials from the same vendor, but with different lot numbers. These check standards were analyzed post calibration and post sample analysis. Each ICPMS measurement was conducted in triplicate and a sample duplicate and an analytical sample spike were performed during each assay.

Arsenic Speciation Analysis

Arsenic speciation was achieved with a liquid chromatography system interfaced to the ICP-MS instrument operated, in a transient acquisition mode. Separation of the arsenic compounds was achieved with a Phenomenex Luna C18 100A column (250 × 4.40 × 5μ) with an isocratic mobile phase of 2.5 mM oxalic acid, 10 mM 1-heptanesulfonic acid (ion-pairing agent), and 0.1% methanol adjusted to a pH of 4 with ammonium hydroxide. The mobile phase flow rate was set at 1.0 ml/min and an injection volume of 30 μl was used. Yttrium prepared at a concentration of 150 ng/ml in the mobile phase was employed as an internal standard. Injection of 10 μl of the internal standard was performed post-column and was necessary since mobile phase and sample salts dampen the signal intensity over the course of the assay. Calibration of the instrument was conducted with reference materials obtained from SPEX Certiprep, Sigma, and Chem Service. Verification of instrument calibration was achieved with preparations of reference materials by a chemist other than the one who prepared the calibration standards. Check standards were analyzed post calibration and sample analysis.

Principal Findings and Significance

Total Arsenic Results

Table 1 presents the results for total arsenic in digested and extracted samples. A significant matrix effect was observed during measurements of total arsenic in digestion-batch one. This was indicated by low recoveries of the digestion matrix spike, digestion certified reference material (SRM), and the analytical spike. Therefore, a method of standard addition was performed on one sample, the matrix spike, and the SRM. Digestion quality controls were much improved under these conditions and confidence in the final arsenic result was obtained. When a smaller digestion mass was utilized in digestion-batch 2, the matrix effect was not observed and method of standard addition was not necessary.

Table 1. Total arsenic results for digested and extracted algae samples.

	Arsenic (mg/g)	Digestion / Extraction Duplicates (%RSD / %RPD)	Matrix Spike / Reagent Blank Spike (% Recovery)	Dogfish Muscle (DORM-2) SRM (% Recovery)
Digestion-Batch 1	13*	5.3%	60%* / NA	90%
Digestion-Batch 2	10.2	17%	83% / 87%	88%
Extraction 1 (TFA)	5.9	8.0%	NA / 83%	92%
Digestion-Batch 2 (TFA Solids)	4.7	NA	NA	NA
Extraction 2 (MeOH-Water)	2.6	NA	NA / 59%	87%

*Determined by Method of Standard Addition; NA = Parameter Not Available.

Total arsenic analysis of the TFA extract indicated that 51% of the total arsenic was extracted under these conditions. This was further verified by digestion and analysis of the extraction raffinate to account for 41% of the missing arsenic. Analysis of the second extraction (methanol-water [3:1]), accounted for 22% of the unextracted arsenic from the first extraction. By summing the percent arsenic extracted by method one and method two, a total arsenic extraction of 73% was achieved.

Arsenic Speciation Results

Table 2 presents the final results for arsenic speciation of the algae extracts. The TFA extraction blank showed significant arsenate signal with regards to the arsenate signals observed for the samples. Most likely this is due to an argon-chloride interference (Ar40Cl35 at As75). This is also the most likely culprit for the high SRM recoveries for this species.

Please refer to the discussion section of this report for more details. The methanol-water extraction reagent blank spike recovered was low for arsenite, however, this was seen as a low recovery rate for total arsenic in this sample as well. The most likely cause for this low recovery is that the sample was inappropriately spiked with arsenite.

Known arsenic species measured in this experiment were very low and do not account for the majority of arsenic species present in the algae sample.

Table 2. Arsenic speciation results for algae extracts (concentration units mg/g, unless otherwise noted).

	Arsenate (As^{+5}) as Arsenic	Arsenite (As^{+3}) as Arsenic	Monomethylarsinic Acid (MMA) as Arsenic	Dimethylarsinic Acid (DMA) as Arsenic	Arsenobetaine as Arsenic
TFA Extraction Blank	0.21	< 0.1	< 0.1	< 0.1	< 0.1
TFA Algae Extract 1	0.46	0.56	< 0.1	0.11	< 0.1
TFA Algae Extract 2	0.32	0.49	< 0.1	< 0.1	< 0.1
TFA Reagent Blank Spike	105% Recovery	84% Recovery	NA	NA	NA
TFA DROM-2 SRM Extract	323% Recovery	< 0.1	< 0.1	79% Recovery	2% Recovery
MeOH-Water Extraction Blank	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
MeOH-Water Algae Extract 1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
MeOH-Water Algae Extract 2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
MeOH-Water Reagent Blank Spike	117% Recovery	12% Recovery	NA	NA	NA
MeOH-Water DROM-2 SRM Extract	198% Recovery	< 0.1	< 0.1	85% Recovery	97% Recovery

Discussion

Data obtained in this experiment are inconclusive if TFA is the best solvent for extraction of arsenic species in algae. This solvent extracted only 51% of the total arsenic contained in the algae sample. In addition, recoveries of arsenobetaine in the SRM were extremely low and reagent blanks for arsenate in this solvent were significant with regards to sample. Smith et al. (2008) reported success with TFA extraction of rice plants; however, there is no mention of extraction blanks, and/or extracted SRMs, and the research was only concerned with arsenate, arsenite, monomethylarsinic acid (MMA), and dimethylarsinic acid (DMA) (1). The use of a chloride interference correction may remedy the issue (see below discussion on interference corrections); however, the efficacy of this solution has not yet been demonstrated. Kohlmeyer et al. (2002) reports that marine algae lack arsenobetaine and contain mostly arsenosugars (2). Given that, the effect of TFA may be a moot point; however, there is still concern that TFA will affect arsenosugars and one wonders, what is happening to the arsenobtaine? Increasing the current arsenic speciation data acquisition time and re-analyzing the TFA extracts to look for later eluting arsenic compounds may be an experiment worth conducting. In addition, setting up the current LCICPMS system to run arsenosugars would also be a direction worth heading. However, obtaining arsenosugar reference materials may prove futile (see discussion on reference materials).

Methanol-water (3:1) extracted arsenic species that were unextractable with TFA. The reagent blank indicated that the reagents used to prepare the extraction fluids produced less interference. This result was further demonstrated by a lower recovery of arsenate in the SRM extracted by methanol-water than that obtained for TFA (198% versus 323%). Arsenobetaine recoveries using the methanol-water extraction procedure were much superior to the TFA extracted counterpart, and the DMA extraction recovery was greater as well. Increasing the current arsenic speciation data acquisition and re-analyzing the methanol-water extracts to look for later eluting arsenic compounds may be an experiment worth conducting. Also, setting up the current LC-ICPMS system to run arsenosugars would be a direction worth pursuing.

Observation of the argon chloride interference warrants concern. Often, this can be corrected by subtraction of the reagent blank; however, since chloride is anticipated to be variable in samples, this practice is unacceptable. Another approach to this issue is to utilize an interference correction equation. Arsenic is monoisotopic with an atomic mass of 75 Daltons. Chloride has two isotopes, 35 Daltons and 37 Daltons, with relative abundances of 75.53 and 24.47, respectively. If the signal is monitored at mass 77 Daltons (Ar40Cl37), then an interference equation can be employed to correct for the interference. However, one must still beware because selenium also has an isotope at 77 Daltons with a relative abundance of 7.58. Therefore, monitoring selenium at mass 82 would allow one to correct for selenium interference at the Ar40Cl37 mass. Still, we are not out of the woods—krypton has an isotope at mass 82 as well, with a relative abundance of 11.56. Krypton is typically found alongside argon, and because it is heavier than argon, its presence becomes more prevalent as the liquid argon tank for the ICP-MS depletes. Therefore, another correction can be made if we measure krypton at mass 83. Putting all the interference equations together results in an expression as follows:

$$\text{Mass 75 signal} - \{3.1 \times \text{mass 77 signal} - [0.82 \times \text{mass 82 signal} - (1.0 \times \text{mass 83 signal})]\}$$

The signal coefficients are generated from the ratio of the relative abundances of the elements. Use of interference equations are commonplace in routine ICP-MS analysis, however to date we know of no speciation assays that utilize them. Analysis of extracted blanks and extracted SRMs under these conditions would provide a measure of success or failure to this approach. Regardless, it is fun to think about.

Without the appropriate arsenic reference materials, identification of other arsenic compounds by the current speciation method is not possible. One option is to contact Professor K.V. Francesconi and inquire if he would be willing to share the four arsenosugars that are in his possession (Madsen et al. 2000). Another option would be to locate synthesis methods for several of the most probable arsenic sugars present, as reported by Kohlmeyer et al. (2002), and prepare them in-house. A third option could be to contact a chemical manufacturer and request to have the most probable arsenic sugar compounds custom made, however chances are that this option would be costly. A fourth option, would be to set-up an arsenic speciation method identical to the McSheehy and Szpunar (2000) methods and identify unknown arsenic compounds relative to the known arsenic compounds.

Addendum: Further Experiments to Improve Speciation

The data from the above experiment indicated that the algae sample contained 10 μg/g total arsenic. This value agreed well with data obtained from the independent analyses conducted for The Nature Conservancy for samples collected in Hawaii. A preliminary arsenic extraction experiment performed with trifluoroacetic acid (TFA) as the solvent and duckweed, a marine type plant in Illinois, as the sample showed some promise. However, extraction by this method on the Hawaiian algae sample was only able to recover 51% of the total arsenic. A second extraction with methanol-water performed on the raffinate from the first extraction was able to remove about 55% of the remaining total arsenic. Arsenic speciation of the extracts from these experiments by liquid chromatography inductively coupled plasma mass spectrometry (LC-ICPMS) indicated that the forms of arsenic present were not amendable to the current instrumental methods employed at ISTC. Furthermore, the extraction method was shown to cause changes in the forms of arsenic present.

Objective

To extract arsenic compounds from algae samples by a solid-liquid extraction method. To determine the arsenic species present in the algae extract and their representative concentrations by LC-ICPMS.

Sample Preparation and Total Arsenic Digestion

The sample preparation used in this experiment was similar to that detailed above. The processed sample was stored at –20°C when not in use. Total arsenic result used for calculating recoveries was based on the earlier experiment.

Extraction Methods

To prepare the algae sample for arsenic speciation analysis by LC-ICPMS, solid-liquid extractions were performed. A quarter-gram of homogenized sample was treated with 5.0 ml methanol-water (3:1) at 55°C for 1 hour. The extraction solvent was collected and the procedure was repeated two more times and the extraction fluids were pooled. Eight milliliters from the pooled extract were removed and the methanol was evaporated under a gentle stream of nitrogen at 50°C. Following methanol removal, the sample was diluted to 8.0 ml with 0.2% hydrochloric acid. The final sample was then filtered through a 0.2 μ syringe filter to remove any solids. A reagent blank, an inorganic arsenic matrix spike, a certified dogfish muscle sample, and a commercially available kelp sample purchased locally were processed in parallel to verify sample extraction.

Total Arsenic Analysis

Total arsenic analysis was performed with a VG Elemental PQ Excel ICP-MS. Yttrium was utilized as an internal standard and the instrument was calibrated daily with reference materials procured from SPEX Certiprep. Verification of instrument calibration was achieved with preparations and analysis of two independent reference materials from the same vendor, but with different lot numbers. These check standards were analyzed post calibration and post sample analysis. Each ICPMS measurement was conducted in triplicate and a sample duplicate and an analytical sample spike was performed during each assay.

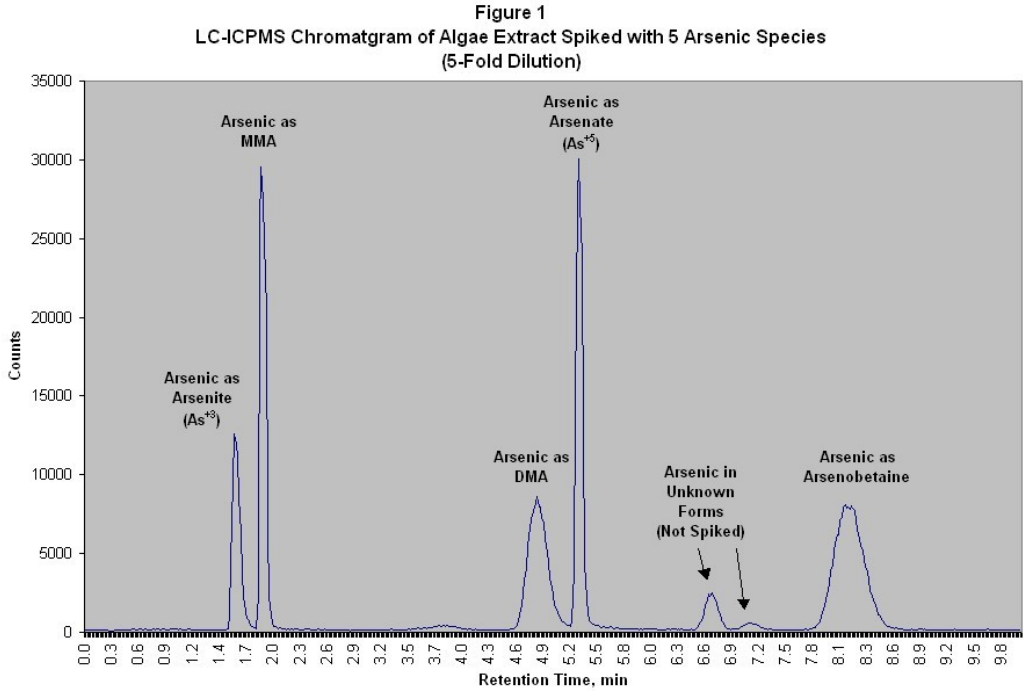
Arsenic Speciation Analysis

Arsenic speciation was achieved with a liquid chromatography system interfaced to the ICP-MS instrument operated in a transient acquisition mode. The LC operating parameters were obtained from a reference method designed for marine biota (1). Separation of the arsenic compounds was achieved with a Thermo AS7 column (4 mm × 250 mm) with a nitric acid gradient mobile phase containing 0.05 mM benzene-1,2-disulfonic acid dipotassium salt (ion-pairing agent) and 0.5% methanol. The mobile phase flow rate was set at 1.0 ml/min and an injection volume of 30 μl was used. Yttrium prepared at a concentration of 100 ng/ml in the mobile phase "A" was employed as an internal standard. Injection of 10 μl of the internal standard was performed post-column—necessary since mobile phase and sample salts dampen the signal intensity over the course of the assay. Calibration of the instrument was conducted with reference materials obtained from SPEX Certiprep, Sigma, and Chem Service. Check standards were analyzed post calibration and sample analysis.

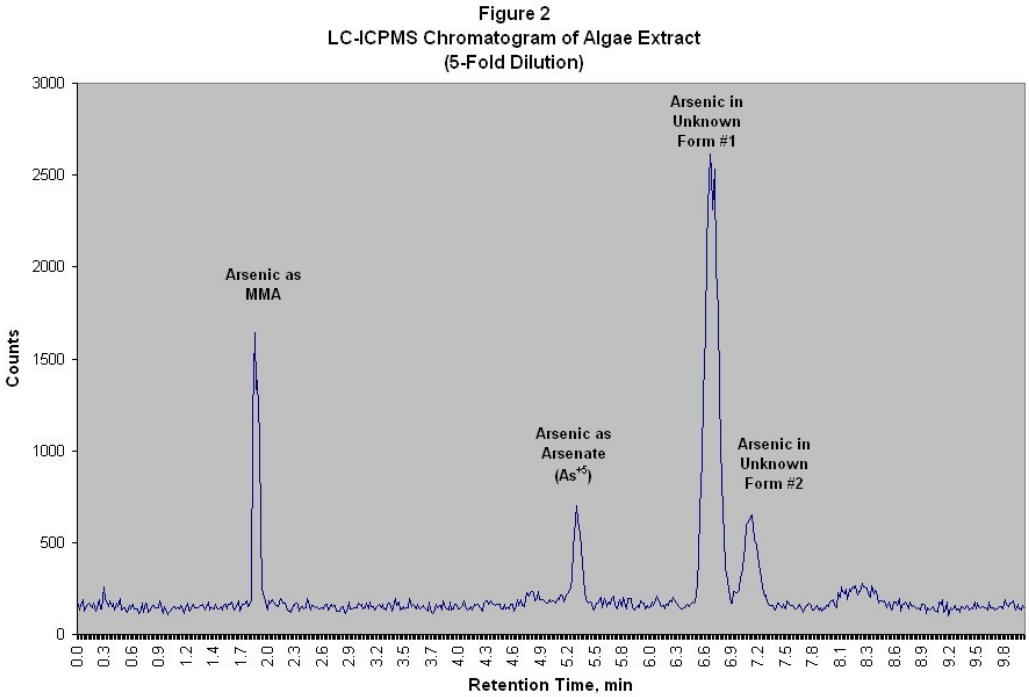
Total Arsenic in Algae Extract Results

Total arsenic analysis of the methanol-water (3:1) extracts was achieved by ICP-MS. The average total arsenic result obtained for duplicate extract of the Hawaiian algae is 11 μg/g. The average total arsenic result obtained for duplicate extract of the kelp is 65 μg/g.

Arsenic Speciation Results



Addendum Figure 1. LC-ICPMS chromatogram of the algae sample spiked with five arsenic species at a five-fold dilution. Recoveries for the five arsenic species spiked in an algae extract recovered from 84% to 106%. In addition, two unknown arsenic species were observed at retention times 6.7 minutes and 7.1 minutes. These unknown peaks were not observed in reagent blanks or calibration standards.



Addendum Figure 2. LC-ICPMS chromatogram of an alga extract with no species spike.

Addendum Table 1. Final arsenic species results for algae extracts.

	Total Arsenic* (µg/g)	Arsenite (µg/g)	MMA (µg/g)	Unknown Species #1 (µg/g)	DMA (µg/g)	Arsenate (µg/g)	Unknown Species #2 (µg/g)	Unknown Species #3 (µg/g)	Arseno-betaine (µg/g)	Species Sum (µg/g)
Gracilaria salicornia (from Hawaii)	11	<0.3	1.2	<0.3	<0.3	0.33	5.5	0.75	<0.3	7.7
Kombu, Family Laminariaceae (purchased locally)	65	<0.3	27	20	9.9	6.4	6.5	<0.3	<0.3	69

*Total arsenic in extract measured by ICP-MS.

The only known arsenic species observed in the extract were arsenic as MMA and arsenic as arsenate. In addition, two unknown forms of arsenic were observed in the extracts. Unknown species #2 was found at the greatest concentration. Table 1 presents the final results for arsenic speciation of the algae extracts. Final results are reported as arsenic in concentration unit µg/g.

Discussion

Total arsenic analysis of the methanol-water (3:1) algae extract indicates that all of the arsenic present in the algae sample was extracted. The sum of the arsenic species accounted for 70% of the arsenic present in the extract. Two known forms of arsenic were present in the algae extract. Two unknown species of arsenic were detected in the extract. One of the Unknown species (#2), is the most abundant form of arsenic in this sample. The remaining 30% of the arsenic present in the extract is not detectable by this LC-ICPMS method.

Analysis of total arsenic in the edible kelp sample produced a total arsenic result of 65 µg/g. This result is almost six times greater than the Hawaiian algae sample. The sum of the arsenic species indicates that all the arsenic present in the edible kelp was accounted for by the LC-ICPMS method. Two unknown forms of arsenic were detected in the edible kelp sample. One of the forms, Unknown species #2, was identical to one observed in the Hawaiian algae sample. The concentration of this form in the edible kelp was similar to the concentration of this unknown form in the Hawaiian algae sample.

Identification of the unknown arsenic species present is impossible by these methods. In order to isolate and identify these unknown species, separate methods would have to be developed. Edmonds et al. (1987) was able to isolate and identify unknown forms of arsenic in the edible seaweed *Hizikia fusiforme*, however the method used were extremely labor intensive (2).

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Determination of groundwater fluxes and evaluation of water-level data to characterize effectiveness of low-permeability valley-fill deposits in the Pearl Harbor Aquifer area

Basic Information

Title:	Determination of groundwater fluxes and evaluation of water-level data to characterize effectiveness of low-permeability valley-fill deposits in the Pearl Harbor Aquifer area
Project Number:	2012HI412S
USGS Grant Number:	G12AP20133
Sponsoring Agency:	USGS
Start Date:	9/1/2013
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Funding Source:	Supplemental
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Supply, Models
Descriptors:	
Principal Investigators:	Aly I El-Kadi

Publication

1. There are no publications.

FINAL REPORT

Determination of Groundwater Fluxes and Evaluation of the Effectiveness of Low-permeability Valley-fills in the Pearl Harbor Aquifer Area, Oahu

May 2015

Aly I. El-Kadi

Kolja Rotzoll

WRRC-2015-06

Project Number: 2012HI412S

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Introduction

The Pearl Harbor Aquifer is the most important aquifer on the island of Oahu and currently supplies about 100 mgd of fresh groundwater mainly for public use (Rotzoll et al. 2010). Decisions related to future infrastructure development and alternate sources of freshwater, including desalinization, depend on the long-term sustainability of the groundwater resources in the Pearl Harbor Aquifer.

For proper resource management it is critical to have an accurate understanding of the groundwater flow through the Pearl Harbor Aquifer. That is: (1) quantification of groundwater fluxes to the Pearl Harbor Aquifer from adjacent groundwater areas, and (2) evaluation of the effects of local hydrogeologic features, in particular low-permeability valley-fill barriers.

Stream valleys filled with alluvium below the water table act as hydrologic barriers to cross-valley groundwater flow because the deposits have a lower permeability than the adjacent basalt. Weathered basalt underneath the streambed contributes to the permeability contrast under the valley fill with respect to the otherwise high-permeability basalt aquifer. Water levels that differ by several feet on opposite sides of a valley-fill indicate an effective barrier. The effectiveness of a valley fill to impede horizontal groundwater flow depends on the geometry and hydrologic parameters of the deposits (Oki 2005, Rotzoll and El-Kadi 2007).

Problem and Research Objectives

The scope of work includes (1) developing a regional numerical groundwater model that quantifies groundwater fluxes to the Pearl Harbor Aquifer from adjacent areas, and (2) analyzing groundwater-level data to evaluate the hydrologic effectiveness of valley-fill barriers, including those associated with Waimano, Waimalu, and Kalauao Streams.

Methodology

Groundwater fluxes to the Pearl Harbor freshwater-lens aquifer include surficial recharge and underflow from adjacent high-level water bodies (Schofield Plateau and dike-impounded water from the rift zones of the Koolau and Waianae Volcano). A three-dimensional island-wide MODFLOW model (Harbaugh et al. 2000) of Oahu focuses on groundwater areas adjacent to the Pearl Harbor Aquifer. The numerical model is capable of simulating groundwater flow and the freshwater-saltwater interface using the Saltwater-Intrusion (SWI) package (Bakker and Schaars 2005).

The model developed for this project incorporates the latest available groundwater-recharge estimates developed by the USGS, recent groundwater withdrawal rates, and aquifer parameters that are based on previously published data. The steady-state model of the recent hydrologic conditions is calibrated using observed groundwater levels, vertical salinity profiles, and estimated base flows of streams. Upon successful calibration, groundwater fluxes into the Pearl Harbor Aquifer can be determined for recent conditions. The effects of predevelopment conditions on the location of the groundwater divide between the leeward and Pearl Harbor side in the Koolau high-level water area can also be tested.

Recent synoptic water-level surveys in the Pearl Harbor Aquifer by the USGS and water levels measured on opposite sides of valley-fills were used to characterize the effectiveness of the alluvium as a hydrologic barrier. Moreover, continuously measured water levels were analyzed to evaluate the cross-boundary effects of groundwater withdrawals. After removing environmental stresses that influence water levels other than groundwater withdrawals (e.g., barometric pressure, recharge events), the water-level time series can be investigated for signs of drawdown and recovery across valley fills.

Principal Findings and Significance

The Saltwater-Intrusion model code was successfully used in one-dimensional cross sections to test the suitability to simulate density-dependent groundwater flow in freshwater-lens aquifer systems. Hawaii aquifers are vastly heterogeneous. To develop an island-wide model, Oahu's complex geology has been reduced to three simplified hydrogeologic units: (1) dike-intruded volcanic rock, (2) dike-free volcanic rock, and (3) sediments and rejuvenated Volcanics. The altitude of the contact between overlying sediments and volcanic rock has been digitized for the entire island to 6,000 ft below sea level, which facilitates the model grid generation of the hydrogeologic units. Published water levels from wells, tunnels, springs, and wetlands on Oahu were compiled to calibrate the numerical model. To date, results have not been finalized as availability of the USGS recharge estimates for Oahu has only been made available on May 2014.

This project has been merged into the island-wide Oahu model (Assessment of Groundwater Availability in the Volcanic-rock Aquifers of Oahu, Hawaii, Project 2014HI439S). See Project 2014HI439S report for details.

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Evaluation of the Impact of Drought Conditions Upon the Waiahole Ditch System Development Tunnels: Ground Water Sustainability Implications Under Adverse Climate Change Conditions

Basic Information

Title:	Evaluation of the Impact of Drought Conditions Upon the Waiahole Ditch System Development Tunnels: Ground Water Sustainability Implications Under Adverse Climate Change Conditions
Project Number:	2013HI415B
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End Date:	2/28/2016
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Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Aly I El-Kadi

Publication

1. There are no publications.

Problem and Research Objectives

Global climate change includes both natural as well as anthropogenic impacts on our climate and hence the hydrologic cycle. Greenhouse gases, followed by the global temperature rises are known to bring about significant temporal and spatial changes in the precipitation and temperature regimes. Freshwater resources, both surface and ground water, are vulnerable to these changes and pose potentially far reaching consequences for the society and the environment. Effects of climate change on surface water has received a fair bit of attention in the research and the ensuing understanding, but that on the groundwater has been lacking more and has been recently gaining interest. Though there will be long-term dynamic linkages between groundwater use, recharge, discharge and the climate; the most direct impact of climate on groundwater is through recharge. Reductions in recharge will cause excessive depletion of valuable groundwater storage.

The research area encompasses the Waiahole Ditch System (Figure 1) and the Pearl Harbor aquifer (Figure 2). In their evaluation of these dike systems, Takasaki and Mink (1985) provide a historical framework of investigations into this phenomenon, with their estimate at the time, of 560 billion gallons of storage occurring within the primary recharge area of the Koolau Mountains—with no recharge estimate provided at the abutment to Pearl Harbor. It is estimated that reductions in recharge due to adverse climate change will affect the predominant base flow contributions from the Waiahole Ditch System development tunnels, re-kindling competition for this valuable resource among leeward and windward interests. Adverse climate change influences manifest by Waiahole Ditch discharge reductions will also have its associated impacts upon the groundwater flow from the high-level dike compartments to the Pearl Harbor basal lens. Demands upon the Pearl Harbor aquifer will continue to increase with pumpage from the renovated HBWS Ewa Shaft, and future development requirements for the Hoopili, Koa Ridge, and Waiawa residential projects, along with the increased home basing of military troops. The latter will require the extended utilization of groundwater resources from among present Department of Defense sources—Waiawa Shaft, Red Hill Shaft, and the Halawa Shaft. Climate change effects on the groundwater flow regime, from dike compartments to basal lens, will escalate many competing demands. A greater understanding of the relationship among the windward high-level groundwater body and the Pearl Harbor basal lens would directly address these future concerns.

This study evaluates the relationship among the high-level windward dike compartment systems and the groundwater basal system of the Pearl Harbor aquifer. The hydrologic mechanisms of the movement of high-level groundwater to the basal lens are governed by two theoretical principles—laminar flow Darcy theory within the high-level dike compartments, and the Ghyben-Herzberg theory within the Pearl Harbor basal lens. Shallow index monitor wells in the basal lens (Fig. 2) would indicate the earliest temporal responses to groundwater movement— specifically direct recharge, originating from dike compartments.

Through assessment of the relationship between the high-level groundwater dike compartments under prior drought conditions, and its attendant impact upon the Pearl Harbor basal lens, a proxy of future adverse climate change impacts can be identified. The results of the study are expected to assist policy makers in their preparations for climate change adaptive strategies.

Identifying the temporal dynamics of the dike compartment and basal lens interaction may allow sufficient preparation time for policy makers to program specific capital projects that address adverse climate change consequences.

The study is specifically aimed at evaluating the relationship among rainfall distribution, tunnel discharges, and potential adverse influences upon Pearl Harbor groundwater head levels because of climate change. The impacts upon recharge will not be quantified, but will be proxied by the response of Pearl Harbor index monitor wellhead-levels to the dynamic adjustments resultant from drought conditions. The scope of work will include literature review, data compilation, statistical analysis, monitoring of gauges, development-tunnel discharge measurements, and the evaluation of currently measured Waiahole Ditch discharge rates.

Methodology

A review of the literature and the compilation of period of record data from the inception of the Waiahole Ditch System to the present are being conducted. The data includes precipitation records, Waiahole Ditch System discharge and instrument stage records, HBWS pumpage, deep monitor index well head level records, USGS Pearl Harbor spring discharges, and pumpage data from the Department of Defense and other sources. The study comprises data compilation, Waiahole Ditch System discharge measurements, and the application of statistical methods to assess the research variables. Climate data are used to assess the effects of previous episodic drought conditions upon the discharges of the Waiahole development tunnels, with the perspective of foreseeing sustainability impacts to the Pearl Harbor aquifer that may be attributable to adverse future climate-change conditions.

During this reporting period the previously installed pressure and barometric data loggers at Kahana Tunnel bulkheads A and B, Waihee Tunnel, and Kahaluu Tunnel (Fig. 3) were retrieved. These remote sites were difficult to access and were reached on foot. The data logger with the rain gauge installed at the helipad of the Kahana Tunnel was also recovered. Data from the pressure transducers were downloaded. Statistical analyses of these data and the other data mentioned above are being carried out.

In the next phase of the study, univariate multiple regressions will be used to determine appropriate models that best represent the associations among the research variables. Semi-partial correlations will be assessed to determine its efficacy in isolating unique contributions of a particular predictor variable to a response variable. Contrast coding and other statistical methods may also be applied to identify completely independent contributions among predictor variables. The study will focus on previous episodic drought conditions upon the Waiahole development tunnels discharges with the perspective of foreseeing sustainability impacts attributable to adverse future climate change conditions.

Principal Findings and Significance

It was observed during the data logger retrieval trips up the mountain that the Kahana and Waihee tunnels were actively producing water, but the Kahaluu tunnel was not. The Kahana

bulkhead appeared to be under pressure with the dial gauge showing about 17 psi, while that at the Waihee Tunnel bulkhead showed about 30 psi. The tipping bucket rain gauge near the Kahana Tunnel, which was placed at the edge of a helipad, was found to be clogged with leaves and non-operational. The raw data downloaded from the sensors are shown in Figure 4. The water in Kahana and Waihee tunnels are under pressure. The Kahana tunnel A registered an average pressure of 15.5 psi, just above the atmospheric pressure near that location at 14.3 psi. The bulkhead B at Kahana was slightly at a higher pressure, averaging 18.8 psi. The Waihee tunnel appeared to be under higher pressure, and more productive with an average pressure shown at 30.2 psi during the logged durations of 4-6 months. The data retrieved from the Kahaluu pressure transducer logger showed sub-atmospheric pressure and even during the retrieval of the logger the tunnel appeared to be unproductive. The tipping bucket rain gauge was found to be clogged with leaves and non-operational. This data recorder had also malfunctioned and no rain data could be retrieved.

There appeared to be a very weak positive correlation between the pressure heads observed at Kahana A and Kahana B bulkheads, showing a correlation coefficient of 0.1795 only. The correlation plot is shown in Figure 5. Similarly, there did not appear to be any coherent correlations between the Kahana bulkhead pressure heads and the Waihee pressure heads.

Subsequent analyses of the collected groundwater data is being carried out to achieve the targeted objectives of the project.

Publications Cited in Synopsis

Takasaki, K. J., and J.F. Mink, 1985, Evaluation of Major Dike-Impounded Ground-Water Reservoirs, Island of Oahu, U. S. Geological Survey, Water Supply Paper 2217.

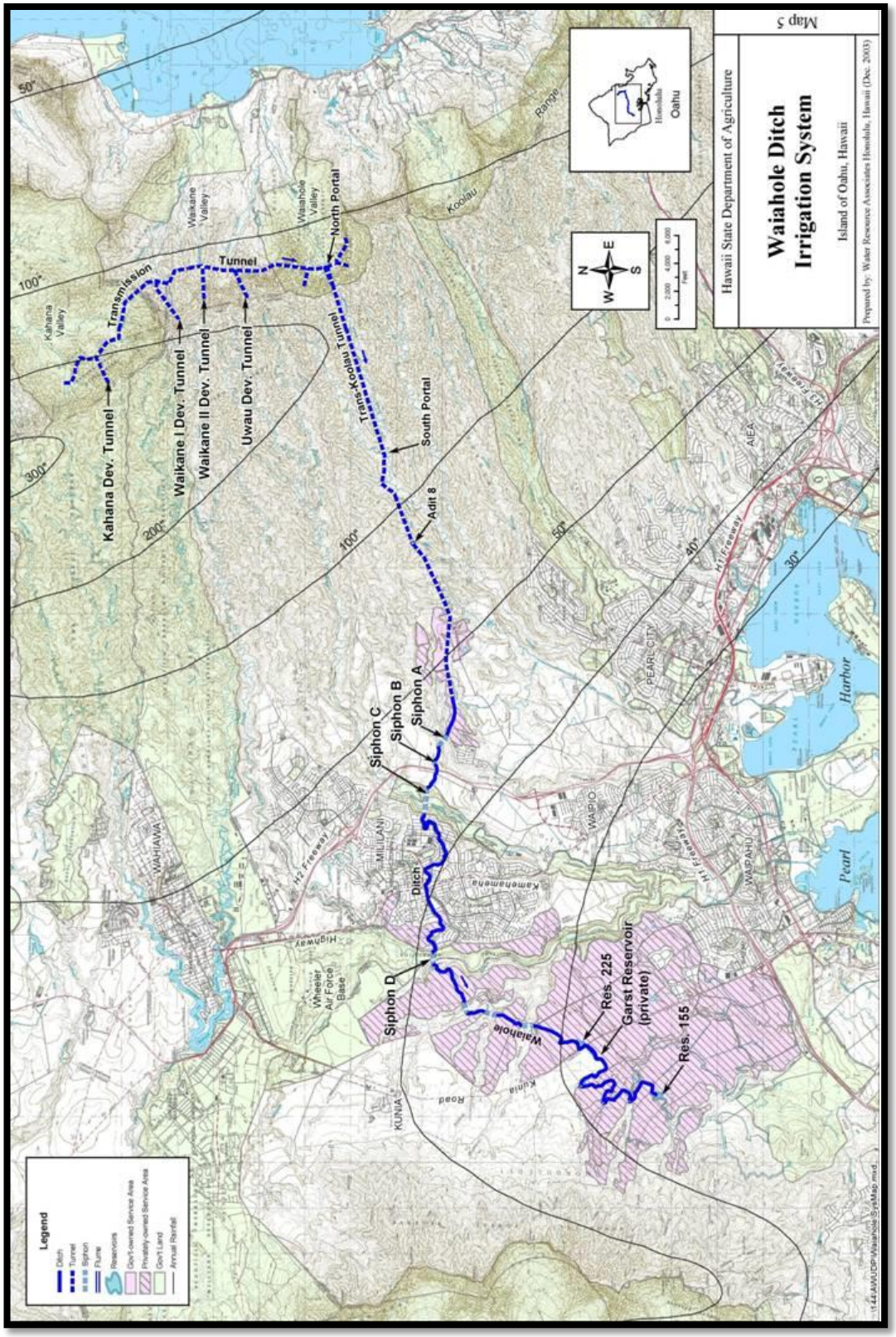

Figure 1. Waiahole Ditch System

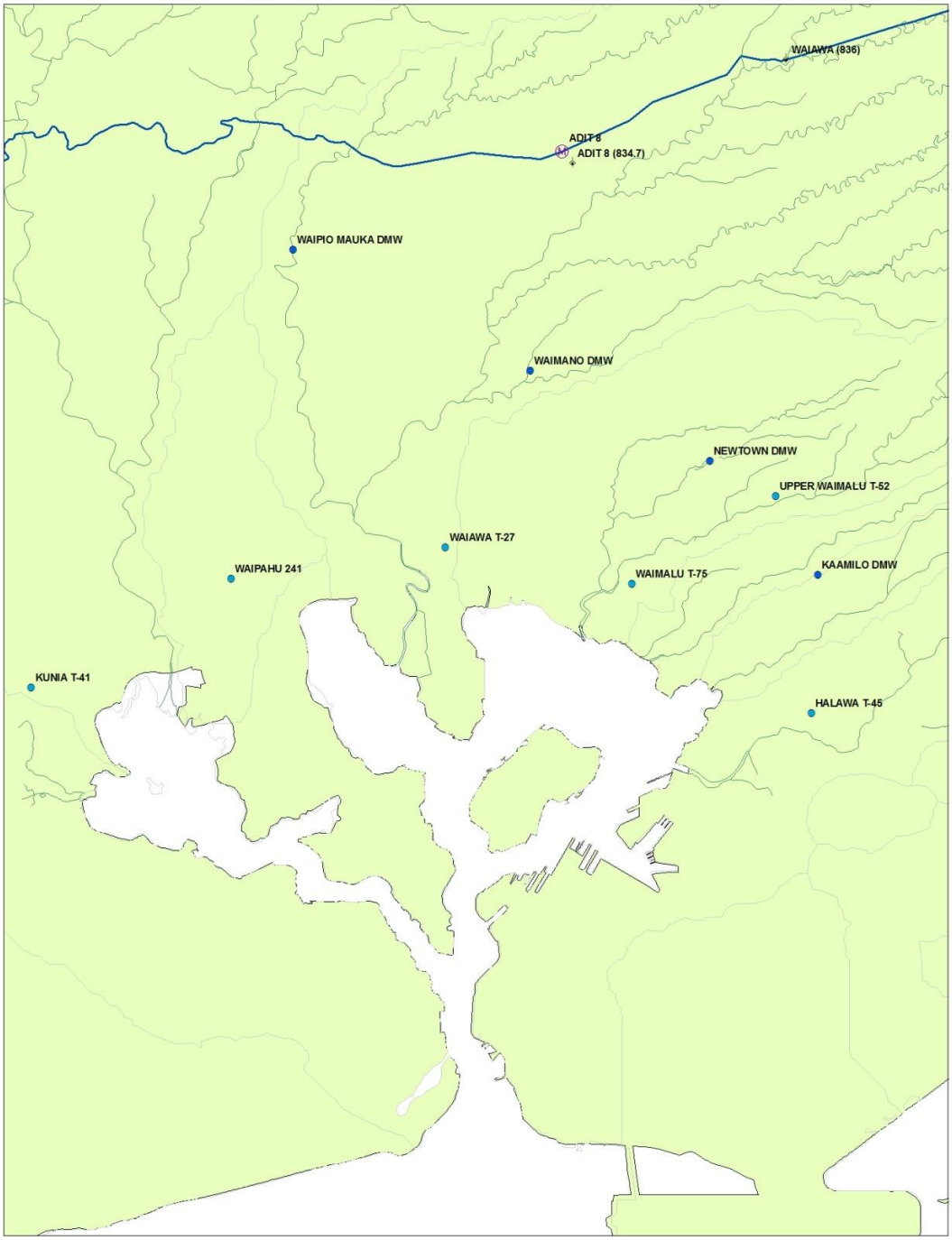

Figure 2. Pearl Harbor Monitor Wells

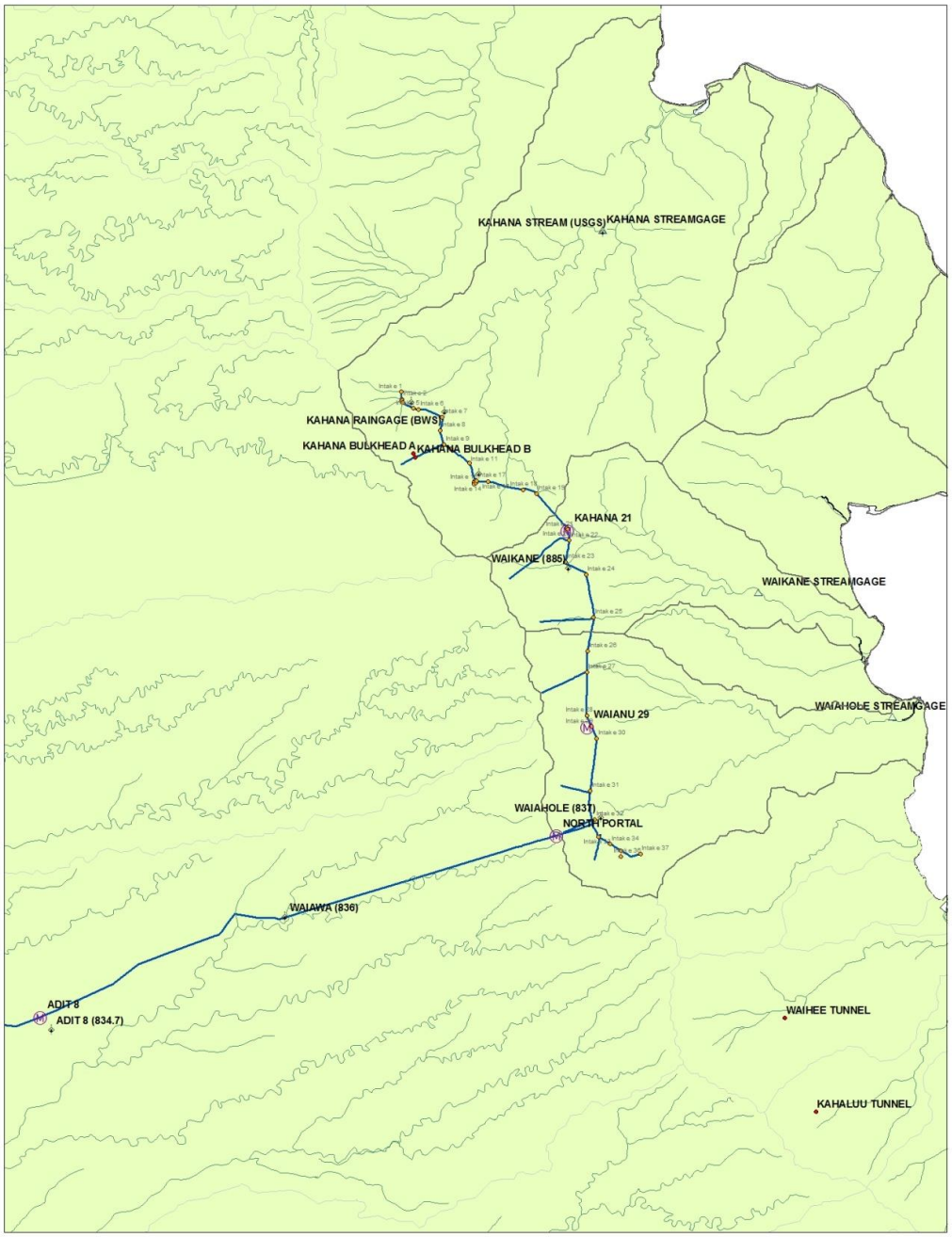

Figure 3. Data collection locations

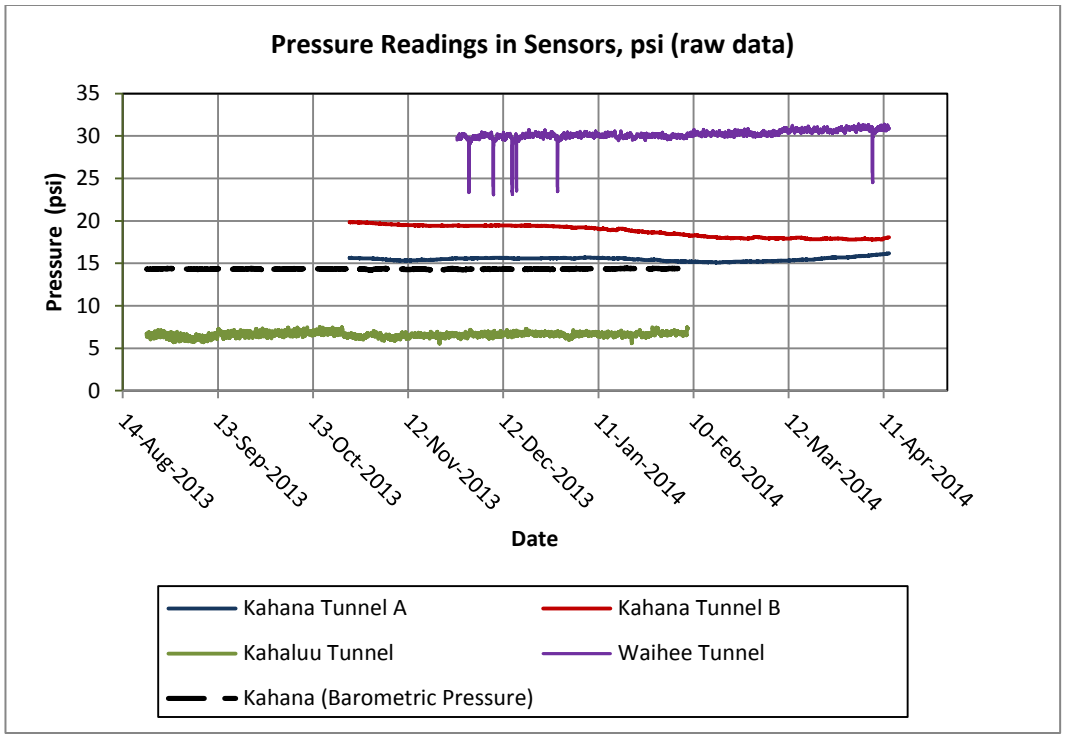

Figure 4. Pressure readings from field deployed pressure sensors located in the bulk heads in 4 locations and a barometric reading at Kahana.

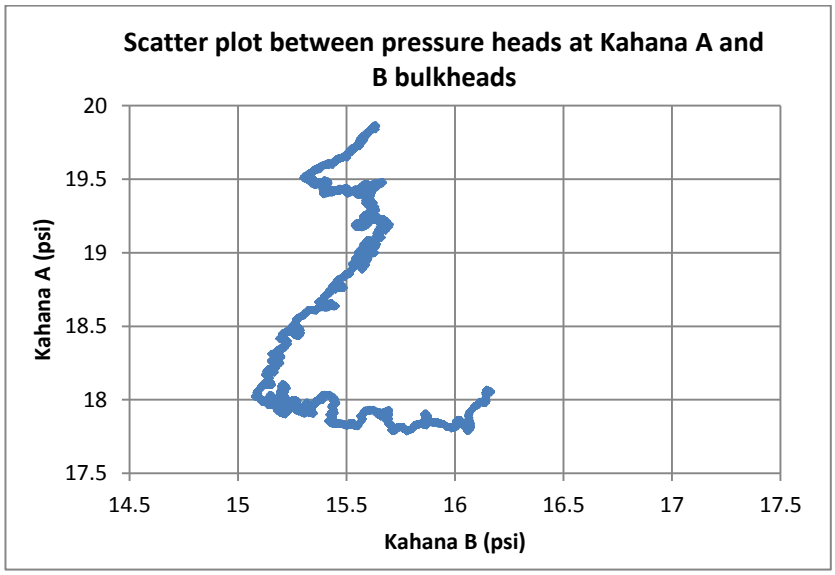

Figure 5. Scatter plot exploring correlation between pressure heads at Kahana A and Kahana B bulk heads (Coefficient of Correlation = 0.1795)

Evaluation of next-generation sequencing technologies for environmental monitoring: characterization of microbial communities from wastewater plants and selected beaches of Hawaii using a metagenomics approach

Basic Information

Title:	Evaluation of next-generation sequencing technologies for environmental monitoring: characterization of microbial communities from wastewater plants and selected beaches of Hawaii using a metagenomics approach
Project Number:	2013HI417B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Water Quality, Methods, Ecology
Descriptors:	None
Principal Investigators:	Marek Kirs, Veljo Kisand

Publications

1. There are no publications.
2. There are no publications for 2014.

Problem and Research Objectives

Microbes are the most abundant and diverse group of organisms on Earth and major drivers of biogeochemical cycles in all environments. Microbial communities are sensitive to change and the quickest to respond. Different viral and bacterial communities are likely to respond very differently to a variety of environmental variables, such as chronic sewage contamination and climate related ocean acidification. As environmental degradation is negatively related to public health and ecosystem services, there is a need to include microbial community based measurements in the current water quality monitoring programs.

Coastal environments are highly complex and diverse. This diversity is maintained by niche availability and disturbances such as periodic terrestrial inputs (wastewater spills, farm runoff) and re-suspension during storm events. These short-term fluctuations, which are highly dependent on coastal land use and infrastructure may mask long-term changes caused by the climate (e.g., directional change) or persistent contamination events (e.g., decreased diversity). Both short-term and long-term changes have important implications for the public as well as environmental health—understanding the structure of coastal microbial communities and their plasticity is important in both contexts. Furthermore, microbial community structure can be used to infer the origin and source of allochthonous material (e.g., microbial contaminants), which is helpful in the management of coastal resources. It would be beneficial to include both environmental and human health perspectives for sustainable management of our coasts.

Currently, research for (1) the effect of environmental change on microbial communities, and (2) the links between microbial water qualities appear as two distinct topics. But evidence exists that the environment and public health issues are closely related. A more holistic approach is needed to fully understand the impact of coastal development and environmental change (e.g., related to climate change or contamination event) on both environmental and public health. Microbial community signatures will not only help us to understand the long-term effects of a given change on coastal environments, but may also address other issues such as contamination sources. This research is aimed as a first step to meeting this goal by describing coastal microbial communities in sewage, how the sewage communities change as they are subjected to the wastewater treatments, and finally the communities found in and around the outfall. Most importantly, this project intends to establish a microbial community baseline to which further studies can be compared.

Molecular methods have been the key tool to study microbial communities because much of the microbial flora is challenging to cultivate. Simple cloning, denaturing gradient gel electrophoresis (DGGE), terminal-restriction fragment length polymorphism (TRFLP), pulsed-field gel electrophoresis (PFGE), and other related techniques have enhanced our understanding of microbial diversity. However, these methods provide only limited information about the microbial community structure and its function because only a limited number of individuals can be identified. Novel next-generation sequencing technologies (NGS), such as pyrosequencing and sequencing-by-synthesis, allow us to explore the microbial community structure in unprecedented detail as millions of sequencing reads are generated for each sample. This exceeds, by roughly, 100,000-fold what was possible in earlier studies when at best a few hundred sequences were analyzed for their taxonomic affiliation from the clonal libraries. Furthermore, relative proportions of different taxonomic groups can be established more reliably by a newer sequencing method. Extremely detailed taxonomic and genetic profiles can be identified for each sample because the whole metagenome (i.e., genetic material present in the

sample) is being analyzed. The next-generation sequencing techniques have become a major tool to study the structural and functional changes of microbial communities in unprecedented detail (Kisand et al. 2012). However, in Hawaii, wastewater and coastal microbial communities have not been studied using this approach, hence we have a limited understanding of the microbial communities in our State.

To maintain a sustainable economy and healthy environment, decisions guiding environmental management need to be based on a broad and comprehensive understanding of the biodiversity and functional capability within the ecosystem (Kisand et al. 2012). Current monitoring programs target a few microbial indicators (such as enterococci) and therefore provide limited understanding of the ecosystem health that is currently explored through other parameters. While it is well established that anthropogenic contamination leads to reduced biodiversity (Vaughan et al. 2001), this aspect is not currently targeted by monitoring programs due to the inherent difficulties of studying microbial communities.

Research Objectives

1. Provide a microbial community analysis for four wastewater treatment plants (WWTP) in Oahu using novel sequencing tools.
2. Provide a microbial community analysis of selected sites along the coastal transect of Oahu using novel sequencing tools.
3. Identify how different wastewater treatments affect microbial communities in the wastewater.
4. Identify whether each major Oahu WWTP ocean discharge has a unique microbial fingerprint
5. Establish a data analysis pipeline for next-generation sequencing data at the University of Hawaii Water Resources Research Center (WRRC).

Methodology

Sample Collection

Water samples were collected from the following four WWTPs on Oahu: Honouliuli (09/2013), Kailua (10/2013), Sand Island (05/2013), and Hawaii Kai (10/2013) (Figure 1). Samples were collected three times within a single week from the raw influent, after primary treatment, after secondary treatment (when available), and from the effluent at each WWTP. Coastal samples were collected along the Sand Island and Waikiki transect at sites routinely monitored by the City and County of Honolulu (CCH), which were in addition to the six sites around the Sand Island outfall (at three different depths with the assistance of CCH) (Figure 2). Additionally, three sets of samples from nine sites along Manoa Stream were collected for the analyses.

After collection samples were cooled on ice, transported to the laboratory, filtered through Supor 200 filters (0.2 µm pore diameter) within 2 hours of collection, and stored at -40 °C. Triplicate filters were prepared from each sample. A total of 231 filters were stored at -40 °C for community analyses.

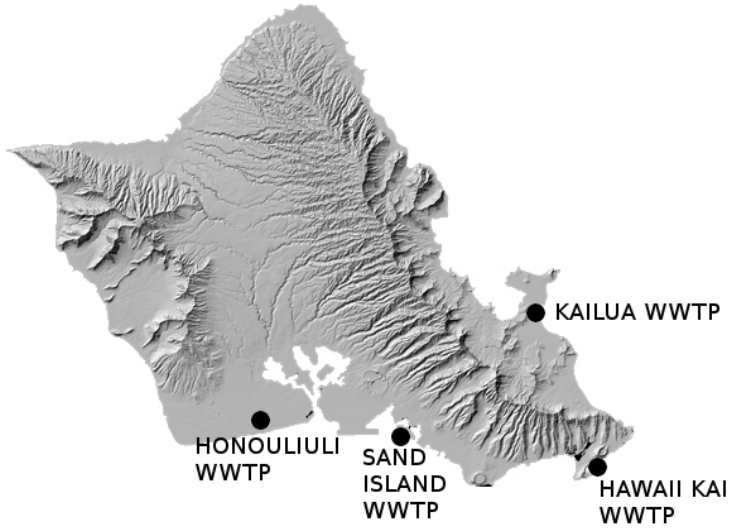

Figure 1. Wastewater treatment plants sampled in this study, Oahu, Hawaii.

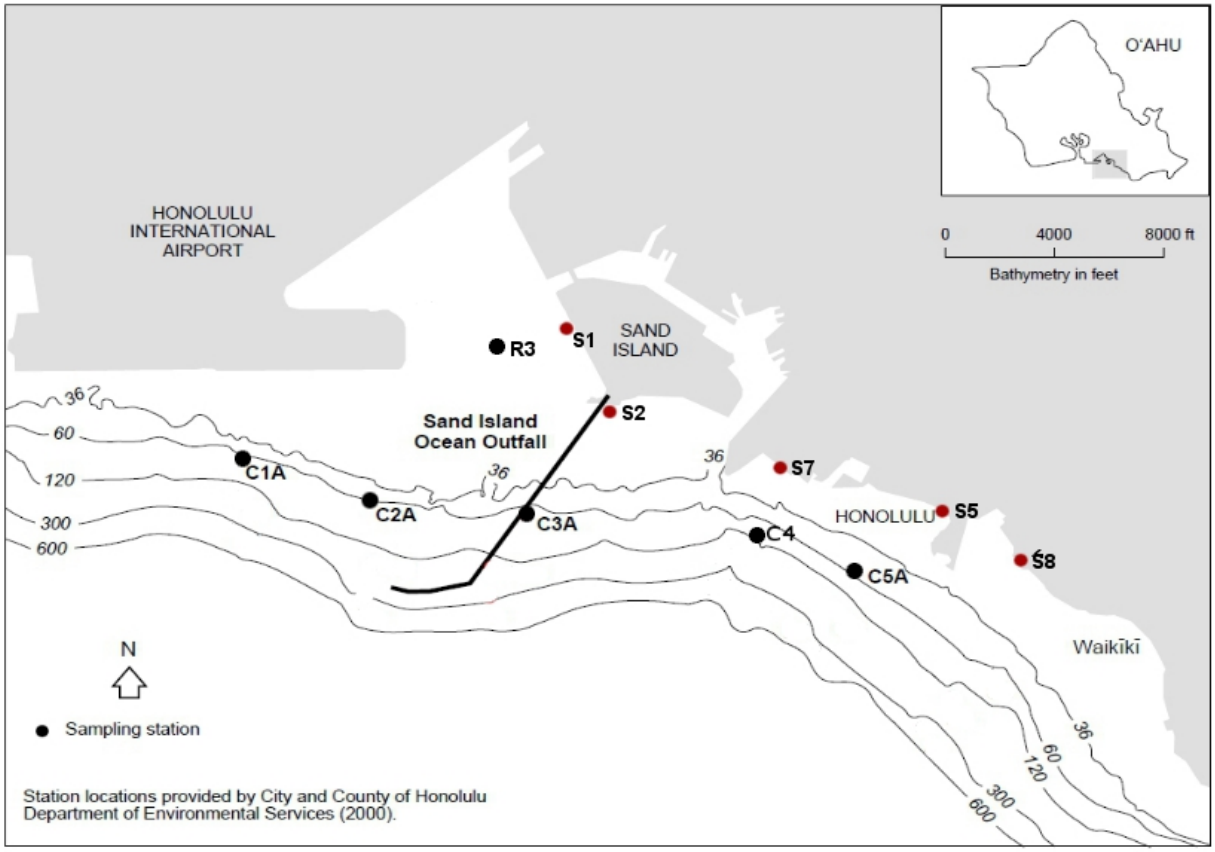

Figure 2. Sampling sites surrounding the Sand Island ocean outfall. Coastal samples were collected along transects C, R, and S. Sites C and R were studied at 3 different depths. NOTE: Samples collected from the shoreline are indicated in red. Sampling sites C = offshore, R = Keehi Lagoon, and S = shoreline.

Sample Collection (Completed)

Concentration of Cultivable Bacteria

Cultivable bacteria were identified and enumerated from samples collected at Sand Island WWTP, around the Sand Island outfall, and selected coastal sites. The samples were placed on marine agar as well as on freshwater and marine water based R2A media (1826-17-1, Difco Lab., Detroit, MI). Over 1,000 colonies were isolated from the plates and stored at -20 °C.

Enterococci concentrations were identified using a standard membrane filtration technique on mEI media (Method 1600; USEPA 2002). The salinity, turbidity, and pH of the samples were also determined.

DNA Isolation (Completed)

DNA was extracted using the PowerSoil® DNA Isolation Kit (MoBio Laboratories Inc., Carlsbad, CA) according to the manufacturer's protocol. Briefly, a frozen filter with the microbiological sample was placed into the Power Bead Tube spiked with 60 µL of solution C1 and vortexed gently. The material was homogenized at maximum speed for 2 minutes on a Mini-Beatbeater-8 (Biospec, Bartlesville, OK) followed by centrifuging at 10,000 × g for 30 seconds at room temperature to remove cell debris. DNA containing supernatant (~500 µL) was transferred into a new collection tube and 250 µL of solution C2 was added. The mixture was vortexed for 5 seconds, and incubated at 4 °C for 5 minutes. After centrifugation for 1 minute at 10,000 × g, the supernatant (600 µL) was transferred into a new 2 mL collection tube and solution 3 (200 µL) was added. The tubes were incubated at 4 °C for 5 minutes, and centrifuged for 1 minute at 10,000 × g. Clean supernatant (750 µL) was transferred into a new collection tube and 1,200 µL of solution C4 was added. Approximately 675 µL of material was loaded onto the Spin Filter and centrifuged at 10,000 × g for 1 minute. This was repeated three times to load the entire DNA into the filter. Filters containing the DNA were washed with solution C5 (500 µL) and centrifuged for 30 seconds at 10,000 × g. After solution C5 was removed, tubes were centrifuged at 10,000 × g for another minute to dry the column and remove the remnants of solution C5, which could interfere with the next step (library preparation and next-generation sequencing). Columns containing the spin filter were carefully placed into new 2 mL centrifuge tubes and the DNA was eluted using solution C6 (100 µL) for 30 seconds at 10,000 × g. The extracted DNA from all the samples was stored at 4 °C until a library was prepared.

Sequencing Library Preparation, Sequencing, and Analyses (Ongoing)

Microbial community composition is currently being determined and evaluated. We are using methodology outlined in Caporaso et al. (2012), which utilizes barcoded primers to target the variable V3 region of the 16S RNA gene. The barcoded library from the 100 samples has been sent for sequencing on the Miseq sequencer (Illumina, San Diego, CA) using the V3 chemistry at the Genetics Core Facility at the Hawaii Institute of Marine Biology (HIMB), University of Hawaii. The balance of the samples will be sequenced when the results from the first batch have been processed and returned. We are expecting close to one billion sequences from this effort. These sequences will be analyzed using the sequence analyses pipeline at WRRC. Briefly, demuplitplex sequences will be filtered to remove low quality reads and clustered using a modified script allowing zero mismatches between the paired reads using cd-hit-otu (Li et al. 2012). Phylogenetic affiliation of the operational taxonomic units (OTUs) will be determined at 97% identity to the reference database SSU Ref NR 119 (http://www.arb-

silva.de/projects/ssu-ref-nr/) using an SINA aligner (Pruesse et al. 2012). Perl script, developed in house, will be used to link cd-hit-otu and SINA outputs to generate the diversity matrixes for analyses. Vegan package in R (http://vegan.r-forge.r-project.org/) will be used to evaluate alpha rarefaction and beta diversity, as well as to conduct de-trended correspondence analysis (DCA) and test (envfit method) associations between the microbial community composition and different parameters.

Principal Findings and Significance

Objectives 1 to 4 (Ongoing)

Concentrations of cultivable bacteria identified from the samples collected at the Sand Island WWTP, and samples from the area surrounding the outfall and the coastal areas are summarized in Table 1. There was good agreement between the enterococci concentration estimates identified by CCH and WRRC scientists. High concentration of enterococci was identified in the samples collected from shoreline sample S8 and from offshore sample C5. It remains to be seen whether the parallel sequencing tools will be able to establish a link between the elevated enterococci concentrations and a terrestrial input or a WWTP outfall influence.

We explored the option to sequence longer DNA fragments because the current sequencing instrument capabilities have improved since the project started, to the extent that better taxonomic resolutions are now possible. We used a novel forward primer (341F), known to be highly specific to a wide range of eubacteria (Klindworth et al. 2013). Unfortunately, the library that was constructed using this novel primer set could not be sequenced due to the primer incompatibility with the sequencing hardware (C. Castaldi, Yale School of Medicine, personal communication; Illumina Sequencing support, personal communications). Currently, a new sample library is in the sequencing queue at the Genetics Core Facility at HIMB. We expect the analyses of all samples to be completed by September 2015. Close to one billion sequences are expected from the two sequencing runs.

Objective 5 (Completed)

We have established a full post-sequencing analyses pipeline at the WRRC environmental microbiology laboratory. We are routinely building barcoded sample libraries for sequencing in our laboratory and are able to compile diversity matrixes within 2 to 3 days, after sequencing is completed

We have established a collaboration with partners at Tartu University and have extended this offer to include two other projects—one exploring the effect of emerging chemicals on microbial communities in slow sand filters, and the second exploring the effect of different soil amendments on microbial diversity and plant growth in soils.

The major goal of this project is to establish a research program to bridge environmental and public health sciences by leveraging novel community analyses tools to target environmental and human health concerns collectively and thereby providing a more holistic view of the coastal ecosystem and promoting sustainable development.

Table 1. Bacterial concentrations in the samples collected at the Sand Island WWTP and surrounding the outfall (offshore, Keehi Lagoon, and shoreline). Enterococci concentrations were determined by the City and County of Honolulu (CCH) and WRRC simultaneously.

Sand Island WWTP	Salinity (ppt)	Enterococci CCH (mEI) (CFU/100 ml)	Enterococci WRRC (mEI) (CFU/100 ml)	R2A (Freshwater)			R2A (Marine)			Marine Agar		
				Day 1 (CFU/100 µl)	Day 2 (CFU/100 µl)	Day 3 (CFU/100 µl)	Day 1 (CFU/100 µl)	Day 2 (CFU/100 µl)	Day 3 (CFU/100 µl)	Day 1 (CFU/100 µl)	Day 2 (CFU/100 µl)	Day 3 (CFU/100 µl)
Influent	5.8	NT	230,000	220,000	280,000	1,440,000	20,000	120,000	140,000	60,000	490,000	600,000
preUV	5.8	NT	17,000	90,000	450,000	780,000	0	50,000	80,000	20,000	110,000	110,000
Effluent	6.1	NT	1,100	0	150,000	190,000	10,000	30,000	30,000	0	60,000	270,000
C1S	33.6	0.9	1	0	0	0	8	72	73	3	9	53
C1M	33.5	<0.9	<1	0	0	0	4	141	129	2	43	110
C1B	33.6	<0.9	<1	0	1	3	16	187	165	2	5	44
C2S	33.6	<0.9	NT	0	1	2	5	12	24	1	31	63
C2M	33.5	<0.9	<1	0	0	6	4	142	264	7	18	35
C2B	33.7	<0.9	1	0	0	1	5	151	154	2	5	14
C3S	33.7	<0.9	<1	1	1	0	5	90	144	1	3	139
C3M	33.8	<0.9	<1	1	1	6	6	78	108	2	3	168
C3B	33.8	<0.9	<1	1	1	0	4	135	206	16	16	125
C4S	33.7	<0.9	<1	0	0	47	0	146	166	4	8	210
C4M	33.8	<0.9	<1	0	0	9	4	66	93	1	7	112
C4B	33.8	<0.9	<1	0	0	11	3	45	70	3	14	95
C5S	33.6	100	154	11	27	0	3	3	8	29	42	112
C5M	33.7	5	10	1	5	9	1	72	98	4	5	14
C5B	33.7	36	36	3	9	4	5	36	35	9	18	26
R3S	33.6	2	4	0	0	144	2	15	35	9	13	19
R3M	33.7	7	3	0	2	78	5	20	31	18	20	32
R3B	33.7	2	7	0	2	19	1	11	29	18	21	31
S1	33.3	3	13	1	8	12	30	66	60	24	34	26
S2	33.2	0.9	<1	0	4	6	33	55	52	13	40	15
S5	33.5	3	28	1	6	18	59	120	120	94	147	50
S7	33.5	9	4	0	0	0	9	46	63	34	54	54
S8	33.4	100	107	8	60	61	98	268	440	168	172	80

Note: C = offshore, R = Keehi Lagoon, and S = shoreline; NT = not tested; the gray background indicates samples biased by overgrowth (yeasts and others).

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Forecasting climate change impacts on watershed-based ecosystem services in Hawaii: A participatory modeling approach

Basic Information

Title:	Forecasting climate change impacts on watershed-based ecosystem services in Hawaii: A participatory modeling approach
Project Number:	2013HI421B
Start Date:	3/1/2013
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	1
Research Category:	Social Sciences
Focus Category:	Methods, Models, Climatological Processes
Descriptors:	None
Principal Investigators:	Steven A. Gray, Ali Fares, Christopher A Lepczyk

Publications

1. Htun, H., S. Gray, C. Lepczyck, K. Adams, S. Conant, and A. Titmus, Predicting Local Scale Climate Change Impacts on Endangered Birds by Combining Watershed Models with Expert Knowledge-based Modeling, Ecological Applications. (in preparation)
2. Gray, S.A., 2013, Decision-support Software for Federal Natural Resource Management Agencies, US Fish and Wildlife and National Park Service webinar series.
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4. Htun, H., S.G. Gray, C. Lepczyk, A. Titmus, and S. Conant, 2013, “Coupling of AnnAGNPS and Fuzzy-logic Cognitive Mapping to Facilitate Endangered Species Management Schemes Under Climate Change Scenarios,” 2013 Hawaiian Wetlands and Waterbird Workshop, Kaneohe, HI.
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FINAL REPORT

Forecasting Climate Change Impacts on Wastershed-Based Ecosystem Services in Hawaii: A Participatory Modeling Approach

May 2015

Steven Gray
Ali Fares
Christopher Lepczyk

WRRC-2015-04

Project Number: 2013HI421B

Water Resources Research Center
University of Hawaii at Manoa
Honolulu, Hawaii

Introduction

The local-scale ecological impacts of global climate change are highly uncertain (Denman et al. 2007, Friedlingstein et al. 2006, Visser et al. 2000). Even though it is widely acknowledged that the impacts of these changes will be felt on the local-level, modeling frameworks which translate these global changes in terms relevant to small-scale ecological decision-makers and natural resource managers remain somewhat elusive given the difficulties in down-scaling and coupling highly complex global processes with highly complex local processes (Denman et al. 2007, Friedlingstein et al. 2006, Sitch et al. 2008). The inability of current modeling methods to make climate change scenarios relevant at the local ecological scale emerges from a general lack of methods that allow resource managers to capture and link these global processes with local-scale dynamics that define the locally relevant connections between climate change, ecological dynamics and natural resource management priorities. Understanding relevant local scale dynamics and providing a way for local decision-makers to anticipate climate change impacts in terms relevant to their management priorities is therefore the key elements for communities that are expected to learn about and collectively adapt to undesired outcomes (Pahl-Wastl and Hare 2004).

Problem and Research Objectives

Climate change in the Pacific Islands provide an ideal context to test ideas regarding the integrating of climate change scenarios, environmental data and expert-based model to understand and predict impacts. Climate change and its macro-effects on temperature, rainfall, sea level and extreme events are likely to bring about localized changes in the coastal zone, agricultural systems, human settlements and infrastructure, water resources, human health, and macroeconomic performance in Pacific Island countries (Barnett 2005, Carter et al. 2001, Easterling 2007). However, local scale ecological dynamic changes brought about by changes in global carbon cycling are currently poorly understood (Denman et al. 2007, Friedlingstein et al. 2006, Sitch et al. 2008) although some general trends have recently emerged (Rosenzweig et al. 2007). For example, recent studies suggest that there will be less frequent but higher intensity rainfall patterns across Pacific Islands due to climate change. Decreases in precipitation and base flow (Chu et al. 2010, Oki 2004), the continuation of these decreasing trends may impact freshwater ecosystems and aquatic species. Decrease in streamflow (Bassiouni and Oki 2012, Oki 2004) may also interrupt movement of native species along streams and may prevent species that spend their larval stages in the ocean from returning to the streams to complete their life cycle (Keener et al. 2012). Invasive plant and animal species are established and expanding in many forests—their responses to climate change will interact with those of native species to determine future ecosystem composition and processes. Native species have to compete with alien species for food and shelter. Existing climate zones are projected to shift, generally upslope, with some eventually disappearing (Benning et al. 2002). The ability of native plant species to adapt to these changes will be affected by competition with aggressive invasion. Available habitat decreases rapidly with elevation, putting species currently found on upper slopes and ridges at special risk (Eiben and Rubinoff 2010, Keener et al. 2012). Currently, native species in their most pristine conditions are located in these regions

with high elevation. Spread of invasive species to these regions is a foreseeable risk caused by climate change.

Although researchers are beginning to synthesize the ecological impacts of these effects cumulatively (Price et al. 2009), information about how habitat managers can mitigate these unwanted outcomes is generally not available. Indeed, climate change has already affected Hawaii by increasing air and sea-surface temperatures that exceed the global average (Giambelluca et al. 2008) and a 10% reduction in streamflow over the last 30 years (Oki 2004). General circulation model projections indicate that continued warming and drying will be paired with more intense, yet less frequent, rainfall events (Chu and Chen 2005, Chu et al. 2010, Norton et al. 2011) and stream flow in some Hawaiian watersheds will continue to be reduced by 6.7% up to 17.2% over the next 40 years (Safeeq and Fares 2011). In addition, erosion regimes and changes in nutrient loading are expected to accompany changes in water availability (Furniss et al. 2010). All of these hydrological and ecological changes to Hawaii's watersheds are thought to be accompanied by decreases in habitat suitability for native species (Keener et al. 2012). However, methods to forecast future changes in terms useful for wildlife management are highly underdeveloped and poorly understood, especially on island communities which are predicted to be disproportionally affected by climate change (Barnett 2005). Insufficient and uncertain comprehension of climate change induced outcomes is thought to limit social adaptation responses (Pahl-Wastl and Hare 2004). Therefore, unique island hydrogeology and climate, together with ambiguous climate change prediction, will add uncertainties and complications to climate change management planning. While it is unknown how watershed and habitat decision-making in the future will be affected by climate changes, poorly-informed decision-making and failure to reduce uncertainty associated with these changes will likely increase the social and ecological costs of climate change on island communities.

Given the difficulties in understanding how water quality and quantity changes will impact habitat, we present a modeling approach intended to provide decision-support by coupling watershed data generated through common models with a relatively novel method of pooling expert knowledge to predict how watershed changes will impact life history functions of managed bird species, mediated by understanding changes in habitat dynamics. To demonstrate the usefulness of this approach to understanding complex habitat changes based on climate change projections in this paper, we use case study data collected from three endangered water birds, Hawaiian Stilt, Coot, and Moorhen, on the Hawaiian Island of Kauai.

Methodology

The modeling framework includes integrating two models in a five-stage process: 1) defining climate change scenarios, 2) modeling watershed changes under climate change scenarios using AnnAGNPS, 3) describing relationships between watershed dynamics and bird habitat using expert-based modeling using Fuzzy-logic Cognitive Mapping (FCM), 4) developing model scenarios by integrating the two models, and 5) using scenario results to discuss adaptation and management strategies.

Climate Change Scenarios

To define climate change reference scenarios we use data from the Intergovernmental Panel on Climate Change (IPCC) report that includes different CO_2 emission rates and their effect on temperature and precipitation changes for the next 100 years. Four CO_2 emission rates, 330 ppm (2003 to 2004 rate), 550 ppm, 710 ppm, and 970 ppm were used for developing model scenarios. In addition, precipitation changes (±5%, ±10%, and ±20%) specific to the Hawaiian Island were also used for scenarios based on previous work (Safeeq and Fares 2011). The model simulations were based on the IPCC's extreme temperature values of the "likely" range (1.1° C and 6.4° C). Mohammad and Ali Fares (2011) previously developed 24 scenarios in Pacific Islands using these three components (CO_2 emission rates, temperature, and precipitation variations), however, only six climate change scenarios (extreme as well as intermediate scenarios) out of these twenty-four were selected as reference models which reduced the complexity of the full combination of all possible scenarios into those that were represented the most variation.

Watershed Model—AnnAGNPS

Empirical data available from different sources were used as model input for the watershed model including: digital elevation model map, soil, rainfall, annual isohyets, land cover, temperature, sky cover, wind speed/direction, and evapotranspiration calculated using the Food and Agriculture Organization method. These data were organized as input files for AnnAGNPS simulation. AnnAGNPS simulated the sediment and nutrients due to primary sources of pollutants found in the Hanalei Watershed which are feral ungulates and alien plants that increase erosion in the upper watershed (increased suspended solids, nutrients and pathogens), cesspools and septic systems in urban areas, agricultural operations (taro ponds), water bird impoundments, and cattle grazing.

Fuzzy-logic Cognitive Mapping

To develop the ecological model based on the knowledge held by local scientific experts and couple it with the climate and watershed model output, we used a FCM program called Mental Modeler (see www.mentalmodeler.org) (Gray et al. 2013). To construct the conceptual expert model, we held a participatory modeling workshop with four local ecologists who were experts in the three species being modeled followed by two individual meetings with scientific experts to refine the model. One FCM was developed for each of the three endemic species that defined relationships between life-history with habitat variables and variables from the watershed models and predator/prey interactions. As a reference for model building, the workshop used Kauai National Wildlife Management Guidelines and a literature search for each of the three species, watershed variables, predator/prey dynamics, and other relevant factors important.

Fuzzy-logic Cognitive mapping (FCM) with the Mental Modeler software includes semi-quantitative models of environmental issues and these models are developed through a three-step process by: 1) defining the important system components relevant to an individual or community, 2) identifying the strength of relationships between component pairs, and 3) simulating scenarios on these models to determine how the system as a whole might react under a range of possible conditions (i.e., system state changes). System components are physical or environmental aspects and may include: 1) attributes or characteristics, 2) elements, or 3) processes of a system or place. They are interconnected to represent complex, direct and

indirect interactions or relationships with one another. Relationships between system components indicate the way one component influences or affects another, such as directionality, strength of the relationship, and type of relationship. Relationship directionality is represented in the FCMs as arrows that start at one component and end at another. The relationship arrows may be one-way (uni-directional) or both directions (bi-directional). The strength of the relationship between components may be classified as High (H; strong), Medium (M; moderate) or Low (L, weak), defined either positively or negatively. Positive effects mean that the component the relationship arrow originates from increases the other component. Negative or inverse relationships mean that the component that the relationship arrow originates from decreases the other component. This effect is represented by a + or a – symbol following the H, M or L strength designation (Gray et al. 2013).

Principal Findings and Significance

Model results based on IPCC scenarios suggest that increased precipitation will increase Stilt abundance, but decrease Coot and Moorhen abundance. On the other hand, decreasing precipitation may have similar effects across all three species. Additionally, our integrated model scenarios suggests that climate change scenarios will impact life functions (e.g., parental success, breeding, foraging success, etc.) differently across the three species. Combining empirical and expert-based conceptual models allows managers to understand the local ecological impacts associated with global climate change, making it relevant to the management scale. Additionally we suggest this framework can be easily employed by wildlife managers to understand the impacts of climate change on different types of animals and across different ecological conditions.

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Quantifying Toxoplasmosis gondii presence in wastewater and freshwater systems

Basic Information

Title:	Quantifying Toxoplasmosis gondii presence in wastewater and freshwater systems
Project Number:	2013HI422B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Acid Deposition, Acid Deposition
Descriptors:	
Principal Investigators:	Christopher A Lepczyk

Publication

1. There are no publications.

Problem and Research Objectives

This proposal addresses the priority issue of Waste Disposal, specifically quantifying the presence of the parasitic disease toxoplasmosis, caused by the parasitic protozoan *Toxoplasma gondii* in streams in Hawaii. *T. gondii* is shed from the body via oocysts in cat feces and is often consumed by other animal species living on land and in the water. In Hawaii, the parasite has been found post mortem in terrestrial and marine animals, including endangered species (e.g., Hawaiian Crow and Red-footed Boobies, Monk Seal). Similarly, off California, toxoplasmosis has been associated with mortality in sea otters (Miller et al. 2008). In humans it can cause serious effects on the unborn, pregnant women, and immunocompromised individuals. Furthermore, toxoplasmosis causes subtle changes in behavior and has been linked to schizophrenia.

Cats, including house cats (*Felis catus*), are the definitive host, meaning that the disease only occurs when cats are present. Transmission of the parasite has traditionally been associated with eating uncooked meat or soil, but it can also be acquired by inhalation from dust, soil, or cat litter, and from water contaminated by cat feces. This project will provide needed information on the public health and environmental risks associated with this waste product in Hawaiian freshwater systems. Quantifying the presence of the parasite in aquatic systems is of great interest to state and federal agencies, including Hawaii's Department of Land and Natural Resources, Hawaii's Department of Health, the U.S. Fish and Wildlife Service, and the National Oceanic and Atmospheric Administration, due to both the human and animal health problems associated with the parasite.

The primary piece of information that will be gained from this research is whether the *T. gondii* oocysts are present in freshwater systems of Oahu, Hawaii. Because marine mammals in the Hawaiian Islands have been found to have toxoplasmosis, it is assumed to be coming via freshwater inputs to the ocean. Determining the presence of oocysts in freshwater systems would provide a pathway linking terrestrial to marine systems for the disease. The information will help form the basis for a larger and more detailed proposal to be submitted for extramural funding. Our findings will help improve monitoring approaches for the disease, provide a baseline set of data about its presence on Oahu, and will be used to develop a more detailed proposal for further defining risk for this disease. Furthermore, our findings have relevance for any Pacific Island or coastal area where cats are present due to the potential presence of the disease and risk to human and animal health.

Because Hawaii has a large number of free roaming cats, there is a large potential for fecal matter to enter the water system both via overland flow and through the sewage system, as occurs in California. Given the human and environmental health concerns associated with the disease, our objective is to determine the presence and relative abundance of oocysts in freshwater streams of Oahu.

Methodology

Within in the lifecycle of *T. gondii*, we will be targeting the oocyst stage, which is the reproductive component shed into the environment. We will test for the presence of oocysts in one to two streams around Oahu by collecting samples both in low flow situations and during

and following any major rainfall event that could lead to increased overland flow or accidental sewage discharge.

We are currently in the midst of constructing the water filter to sample the streams. Upon completion we will field test it and inspect the filtrate for oocysts. If oocysts are detected, then we will use PCR to confirm their presence.

Principal Findings and Significance

Work is still ongoing.

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Impacts of Climate Change on Food Resources of Native Gobiid Fishes and Atyid Shrimp in Hawaiian Streams

Basic Information

Title:	Impacts of Climate Change on Food Resources of Native Gobiid Fishes and Atyid Shrimp in Hawaiian Streams
Project Number:	2013HI423B
Start Date:	3/1/2013
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Ecology, Hydrology, Climatological Processes
Descriptors:	None
Principal Investigators:	Rebecca Ostertag, Richard Ames MacKenzie

Publications

1. Riney, M.H., T.C. Frauendorf, R.A. MacKenzie, P.B. Foulk, and R. Ostertag, 2013, “Using Stable Isotopes and Gut Content Analysis to Assess the Impacts of Climate Change on Food Webs in Hawaiian Streams” in Society for Freshwater Science Conference, Jacksonville, FL.
2. Riney, M.H., T.C. Frauendorf, R.A. MacKenzie, P.B. Foulk, and R. Ostertag, 2013, “The Impacts of Climate Change on Food Webs in Hawaiian Streams” in Tropical Conservation Biology and Environmental Science Symposium, University of Hawaii at Hilo, HI.
3. Riney, M.H., planned December 2014, “The Impacts of Climate Change on Food Webs in Hawaiian Streams,” M.S. Thesis, Tropical Conservation Biology and Environmental Science, University of Hawaii at Hilo, HI. (in preparation)
4. Riney, M.H., T.C. Frauendorf, R.A. MacKenzie, R. Tingley III, P.B. Foulk, and R. Ostertag, The Effects of Varied Stream Flow on Food Webs in Hawaiian Streams, Journal of the Society for Freshwater Science. (in preparation)

Problem and Research Objectives

This project is designed to accomplish the following objectives: (1) provide a food web analysis based on two critical native faunal species in Hawaiian streams along a naturally occurring precipitation gradient, (2) quantify effects of flow rates on food resource availability for both species, (3) determine if resource limitation is leading to interspecific competition, and (4) provide data on the effects of altered flow rates due to climate change, invasive species, and water diversions, that will help assist in conservation and restoration efforts.

Methodology

To meet these four objectives, the field work and the sampling of invertebrates and the food resources was completed by August 2013. The native gobiid fish were excluded due to permitting constraints, and non-native caddisflies were substituted as a proxy for the food web. All samples were analyzed by a mass spectrometer for stable carbon and nitrogen isotope signatures.

Principal Findings and Significance

Analysis of stable isotope signatures ($\delta^{13}C$ and $\delta^{15}N$) and C:N ratios revealed the highest quality (most nutritious, with respect to C:N) food resources available (i.e., biofilm and the chironomid larvae Chironomidae as primary contributors to the diets of the *Atyoida bisulcata* across the gradient, regardless of flow metric or mean annual rainfall (MAR). Secondary contributors (i.e., food resources that contributed to < 20%) to shrimp diets changed from pelagic (filamentous algae [FPOM] and fine and course particulate organic matter [CPOM]) to benthic (leaf bacteria and fine benthic organic matter [FBOM]) food resources as flow decreased. These resources were slightly lower quality than biofilm and chironomids across the gradient. Total weighted C:N (combined biomass and C:N) of all resources sampled declined with decreasing stream flow, influenced mainly by the increased biomass of two resources that are not considered contributors to the diets of *A. bisulcata*: low quality leaf litter in low flow streams and high quality moss in high flow streams. Quantity (biomass and/or total stock) of high quality biofilm, chironomids, FPOM, and CPOM, declined significantly with decreasing stream flow, which is likely influencing the patterns in the decreased fitness in *A. bisulcata* that was also observed in streams across this gradient. This study highlighted the need to develop management strategies to maintain stream flow levels to support healthy communities of native stream fauna. Additional research is needed to identify instream flow values that are based on the impacts to ecological function (i.e., diet, reproduction, and growth).

Monthly rainfall maps for the islands of Kauai, Oahu, Molokai, Maui, and Hawaii, 2008-2010

Basic Information

Title:	Monthly rainfall maps for the islands of Kauai, Oahu, Molokai, Maui, and Hawaii, 2008-2010
Project Number:	2013HI437S
USGS Grant Number:	G13AP00056
Sponsoring Agency:	USGS/HI
Start Date:	6/17/2013
End Date:	6/14/2014
Funding Source:	104B
Congressional District:	HI-ALL
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Hydrology, None
Descriptors:	
Principal Investigators:	Thomas Giambelluca

Publications

1. There are no publications.
2. Frazier, A.G., T.W. Giambelluca, H.F. Diaz, and H.L. Needham, 2015, “Comparison of geostatistical methods to spatially interpolate month-year rainfall for the Hawaiian Islands,” International Journal of Climatology. (in review)
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FINAL REPORT

Monthly Rainfall Maps for the Islands of Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii, 2008–2010

May 2015

Thomas Giambelluca
Abby Frazier

WRRC-2015-03

Project Number: 2013HI437S

Water Resources Research Center
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Problem and Research Objectives

The Hawaiian Islands have one of the most diverse rainfall patterns on earth. The mountainous terrain, the persistent trade winds, the heating and cooling of the land, and the regular presence of a stable atmospheric layer at an elevation of around 7,000 ft interact to produce areas of uplift in distinct spatial patterns anchored to the topography. The resulting clouds and rainfall produced by this uplift lead to dramatic differences in mean rainfall over short distances. Knowledge of the rainfall patterns is critically important for a variety of resource management issues, including groundwater and surface-water development and protection, controlling and eradicating invasive species, protecting and restoring native ecosystems, and planning for the effects of global warming.

The Rainfall Atlas of Hawaii is a set of maps containing spatial patterns of rainfall for the major Hawaiian Islands (Giambelluca et al. 2013). The maps represent the best estimates of the rainfall for a 30-yr period (1978 to 2007). Using the data set developed for the Rainfall Atlas, a set of monthly maps was generated from 1920 to 2007 to allow analyses of year-to-year variations (Frazier 2012). In recent years, it has become apparent that monthly maps from 2008 to 2010 are needed for numerous water-resource investigations being undertaken by federal, state, and county agencies in Hawaii. The updated maps are needed to extend the available rainfall record through 2010 to enable analyses of current hydrological conditions in Hawaii.

Monthly rainfall maps are foundational products used to develop water budgets and estimates of groundwater recharge. Understanding changes in the spatial distribution of rainfall is critical for the protection and management of water resources in Hawaii. Due to Hawaii's small land masses and isolation, water-resource options are limited, making assessment of water availability even more critical to federal, state, and local decision-makers.

The objective of this project was to develop monthly rainfall maps for 2008 through 2010 for the islands of Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii using an approach that was previously used for the Rainfall Atlas of Hawaii.

Methods

Data Collection

Monthly rainfall data were collected up to 2007 for the Rainfall Atlas of Hawaii project. The database included stations from seven different networks (Table 1). To update the monthly rainfall database for the 2008 through 2010 maps, new data from all sources had to be collected. In addition to collecting data from the seven original sources used in the Rainfall Atlas, data from two additional sources were added to the database (Table 2). The data collection was completed by August 2013. Data were collected from 2007 to 2013 for as many stations as possible, with the 2007 data used as a consistency check to combine the updated data with the old data set. Most of the station data were available online; however, some data were only available on hand written paper data sheets and had to be entered by hand. The manual data entry was performed twice (by two different people) to prevent errors during this process. All data were converted into standard units and formatted consistently. Station coordinates were compared with previous records, and updated when necessary. Any new stations (not present in the master record) were assigned state key numbers (SKNs) that were approved by the State Climatologist.

Table 1. 1837 to 2007 data sources for the Rainfall Atlas of Hawaii.

Source	Data Entry	Contact
State	Hand entry	State Climate Office 2525 Correa Rd., HIG 318 Honolulu, HI 96822 (808) 956-2573
NCDC	Download online	National Climatic Data Center www.ncdc.noaa.gov
USGS	Download PDF, enter manually to spreadsheet	United States Geological Survey http://wdr.water.usgs.gov/allsearch.php
RAWS	Download online	Remote Automated Weather Stations Operated by: National Interagency Fire Center Data hosted by: Western Regional Climate Center http://www.raws.dri.edu/
SCAN	Download online	Soil Climate Analysis Network Operated by: US Dept. of Agriculture Natural Resources Conservation Service http://www.wcc.nrcs.usda.gov/webmap
Hydronet	Download online	Contact: Kevin Kodama (National Weather Service) http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php
HaleNet	Personal Communication	Haleakala Climate Network Contact: Mike Nullet, University of Hawaii at Manoa, Department of Geography

Table 2. New data sources collected from 2007 to 2013 (not included in Rainfall Atlas of Hawaii).

Source	Data Entry	Contact
Hawaiian Commercial and Sugar Company	Personal Communication	Hawaiian Commercial and Sugar Company Contact: Mae Nakahata, Director Agricultural Research and Crop Control
Ponoholo Kahua Ranch	Personal Communication	Kahua Ranch Headquarters

Data Quality Control and Gap Filling

Multiple quality control methods were used to scrutinize the data set (see Giambelluca et al. 2013 for method details). To combine the new data with the old data set, the monthly entries in 2007 were compared. Stations were flagged and investigated whenever the 2007 data did not

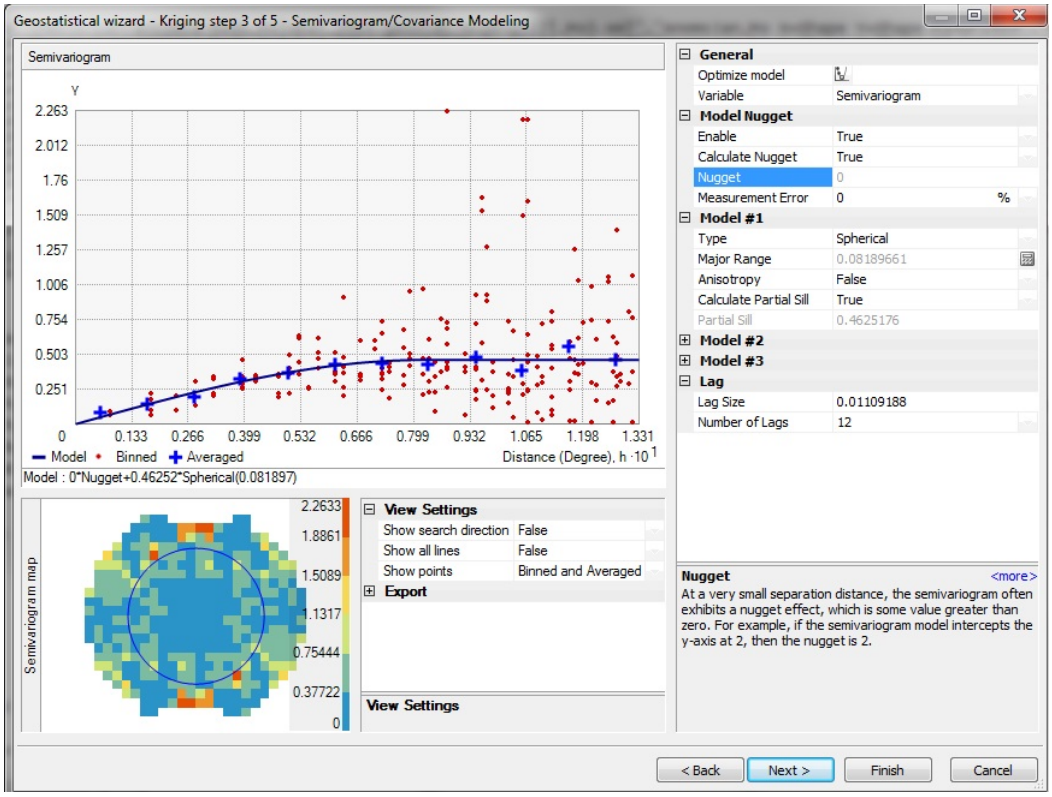

Figure 1. An example of a semi-variogram with a spherical model used in the ordinary kriging process (ArcGIS™ 10.1).

match in the two data sets. To catch errors during the data entry process, any inconsistencies between the two hand-entered data sets were manually verified using the paper records. Homogeneity testing was performed on the full database (including 2012 data) to look for break points due to the addition of the new data. Any missing data were filled using the Normal Ratio method (Paulhus and Kohler 1952) detailed in Giambelluca et al. (2013), and where possible, any long-term stations that had been discontinued were filled to 2012 to maintain the spatial coverage of stations.

Monthly Maps

The monthly maps were generated using the methods established by Frazier 2012. Ordinary kriging, a geostatistical interpolation technique, was used to interpolate rainfall anomalies (deviation from the mean). Relative anomalies (rainfall divided by the mean) were used instead of difference anomalies (rainfall minus the mean). Using the filled data from 2008 to 2012, the monthly station anomalies were calculated relative to the 1978 to 2007 Rainfall Atlas mean. For the island of Kauai, we had to redo the monthly and annual rainfall maps from 1992 to 2012 due to an error found in one station. The anomalies were interpolated for each island in ArcGIS™ 10.1 (ESRI, Redlands, CA, USA), and the semi-variograms were individually modeled for each month-year (Figure 1). The geostatistical layers were converted to

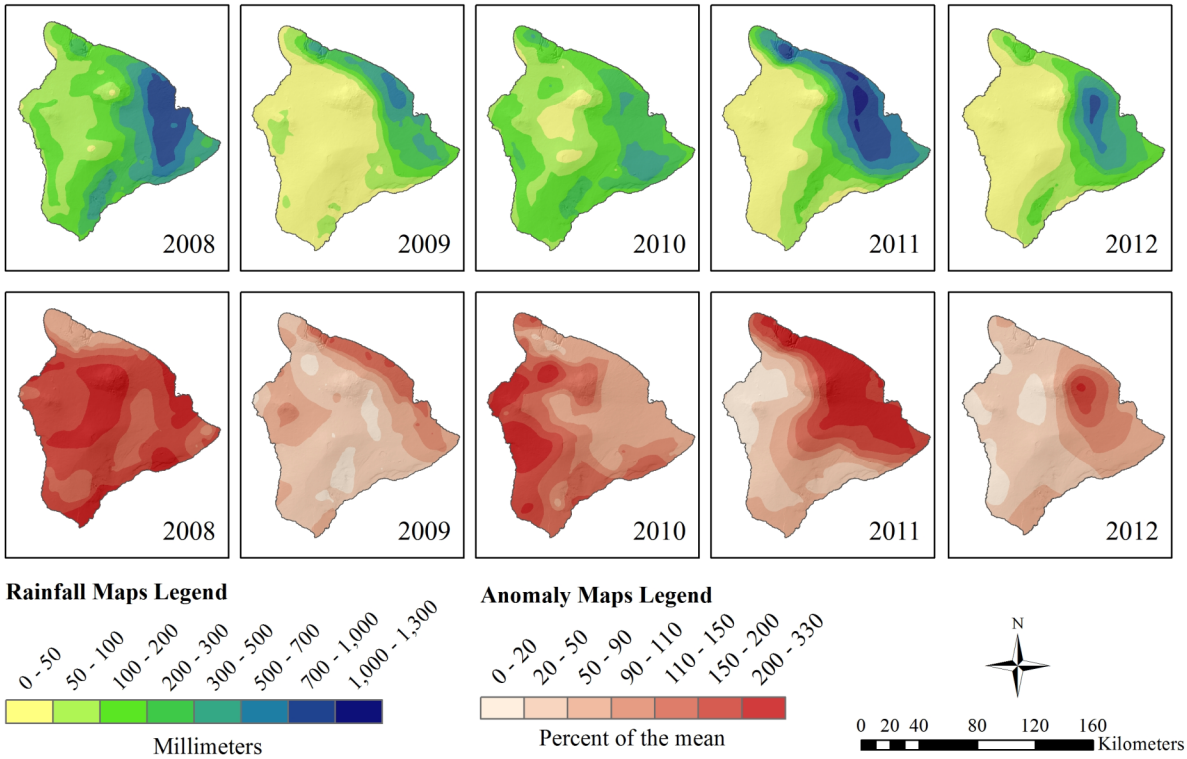

Figure 2. December 2008 to 2012 rainfall maps (top row) and corresponding relative anomaly (estimated value divided by climatology) maps (bottom row) for Hawaii Island.

rasters, and then multiplied by the mean maps to produce the final rainfall maps (a method known as CAI: Climatologically Aided Interpolation, Willmott and Robeson 1995).

Principal Findings and Significance

The monthly rainfall station data was collected from 9 networks from 2007 through 2012. The full monthly database (1837 through 2013) contains 2,224 rain gauge stations, with an average record length of 24 years. These updated data sets (both filled and original observed data) are available for download at the Rainfall Atlas of Hawaii website: http://rainfall.geography.hawaii.edu/downloads.html. Monthly rainfall maps from 2008 to 2012 extended the data set of monthly and annual maps to 1920 through 2012. A total of more than 1,100 maps were produced for this project, including anomaly maps (departures from the 1978 to 2007 mean). An example of the Island of Hawaii's December rainfall and anomaly maps for 2008 to 2012 is shown in Figure 2. All maps have a spatial resolution of 250 m, and are available for download at the Rainfall Atlas of Hawaii website as raster GIS files in inches and millimeters. New maps generated with data from 2008 to 2012 provide information on the spatial rainfall patterns during recent years, which have included some of the driest conditions on record. These maps will be an invaluable resource for updating water budgets and ground water recharge estimates. They will also serve as important inputs for other hydrological and ecological models.

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Assessment of Hydraulic Properties through Tidal Ground-level Analysis for the State of Hawaii

Basic Information

Title:	Assessment of Hydraulic Properties through Tidal Ground-level Analysis for the State of Hawaii
Project Number:	2013HI438S
USGS Grant Number:	G13AP00074
Sponsoring Agency:	USGS
Start Date:	8/5/2013
End Date:	12/31/2014
Funding Source:	104B
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Models, None
Descriptors:	
Principal Investigators:	Aly I El-Kadi

Publications

1. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2014, Development of a hydrogeologic framework from tidal analysis of coastal groundwater levels, Hawaii, 40th American Water Works Association Conference, Honolulu, May 6–9.
2. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2013, Development of a hydrogeologic framework using tidally influenced groundwater levels, Hawaii. Abstract H11H–1248, presented at 2013 Fall Meeting, AGU, San Francisco, CA, Dec. 9–13.
3. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2014, “Up and Down: How can we assess hydraulic properties from tidal fluctuations in coastal aquifers?”, Abstract H53B-0845, presented at 2014 Fall Meeting, AGU, San Francisco, CA, Dec 15–19.

Problem and Research Objectives

The Hawaii aquifers supply water to 1.36 million residents, diverse industries, and a large segment of the U.S. military in the Pacific. With the increase of residential population on the islands, drinking water resources remain limited and are therefore susceptible to impacts from human activity and climate change (Izuka 2013). Decisions related to future infrastructure development and alternate sources of freshwater, including desalinization, depend on the long-term sustainability of the groundwater resources in Hawaii's aquifers.

Numerical groundwater models are becoming standard tools for sustainable development and optimal resource management (e.g., Oki 2005, Gingerich 2008). Identifying relevant components in the hydrogeologic framework and quantifying hydraulic properties for volcanic rock aquifers helps to constrain input parameters for models used in ongoing U.S. Geological Survey (USGS) groundwater-availability and groundwater-resources studies in Hawaii (Izuka 2013). Additionally, evaluating hydraulic properties for coastal sediment aquifers can be beneficial for studies assessing the effects of sea-level rise (e.g., groundwater inundation), including groundwater height in coastal inundation scenarios (Rotzoll and Fletcher 2013).

Ocean-tide signal attenuate through coastal aquifers based on the aquifer's regional hydraulic diffusivity (Jacob 1950, Ferris 1951). Thus, analyzing tidal amplitude decay with distance from the coastline allows estimating regional-scale hydraulic properties and identifying the importance of different hydrologic units (Rotzoll et al. 2013). A few localized studies of tidally influenced groundwater levels in Hawaii exist (e.g., Dale 1974, Gingerich 1995, Oki, 1997, Rotzoll et al. 2008), but a statewide compilation and comparison is lacking.

In this study, aquifer properties were examined in a regional context with respect to the hydrogeologic framework of each island. Hydrologic data exist for some areas in Hawaii, but there has been no effort to synthesize the existing separate efforts into a comprehensive framework for the entire Hawaiian Islands region. The results help to better understand the groundwater flow processes in Hawaii aquifers and facilitate the development of regional numerical groundwater flow and transport models. Water managers and hydrologists benefit from a more detailed characterization of the regional groundwater-flow properties for various purposes (e.g., monitoring, management, and research).

The scope of work covers the large-scale estimation of hydraulic properties of volcanic-rock and coastal-sediment aquifers from tidal attenuation by compiling available data for the state of Hawaii.

Methodology

Tidal attenuation was analyzed by comparing the amplitudes of groundwater level fluctuations occurring on tidal frequencies against the ocean tide amplitudes. This study analyzed existing continuous water-level records, in addition to published tidal-attenuation data from Oahu (Pearl Harbor [Dale 1974], the North Shore [Oki 1997], Honolulu [Rotzoll and Fletcher 2013]), east Maui (Gingerich 1995), and central Maui (Rotzoll et al. 2008). Continuous ocean water level was recorded at several tide gages in Hawaii (National Oceanographic and Atmospheric Administration 2013). Groundwater level records were collected by the USGS and other entities from various wells across the state. Also, unpublished hydrographs from USGS well folders were digitized and compared to historic tides. Although generally short in duration,

tidally influenced constant-rate aquifer test data were digitized from state well-permit applications and compared to ocean tide amplitudes.

Filtering methods to separate water-level fluctuations caused by ocean tides and other environmental stresses, such as barometric pressure and long-period ocean level variations, were explored. For short-term records, several approaches to identify tidal components were examined.

The results of the tidal influence were separated by the island, and by the volcanic rock and the coastal sediment aquifers. The goal is to include the areas that were not assessed comprehensively (e.g., Kauai, Molokai, and the Island of Hawaii). Moreover, groundwater records with little or no tidal influence in coastal areas, allowed identifying areas that have limited hydrological connection to the ocean. Finally, tidally derived aquifer parameters were compared statewide.

Principal Findings and Significance

Hawaii aquifers are extremely heterogeneous. However, they can generally be grouped into three simplified hydrogeologic units: (1) dike-intruded volcanic rock, (2) dike-free volcanic rock, and (3) sediments and rejuvenated Volcanics. The tidal response in groundwater levels can also help to identify these hydrogeologic units and aid in estimating regional hydraulic properties. For example, no tidal signal was observed in the hydrogeologic unit of dike-intruded volcanic rock. It was also found that the lower-permeability caprock unit causes a damping effect for the tidal signal at the boundary. This study combined the volcanic-rock aquifer-diffusivity and the hydraulic conductivity of different regions on each island. The subsequent results were related to the general age of the island. It was demonstrated that hydraulic-conductivity estimates generally decrease with the island age because weathering reduces open pore space and flow paths. The results from this study will be used in the regional island-wide numerical models by the USGS Groundwater Resources Program.

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Evaluation of Portable Multi-use Automated Concentration System (PMACS) for the analysis of indicator bacteria and microbial source tracking markers in Hawaii

Basic Information

Title:	Evaluation of Portable Multi-use Automated Concentration System (PMACS) for the analysis of indicator bacteria and microbial source tracking markers in Hawaii
Project Number:	2014HI428B
Start Date:	3/1/2014
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Methods, Non Point Pollution
Descriptors:	None
Principal Investigators:	Marek Kirs, Roger Fujioka, Philip Moravcik

Publication

1. Kirs, M., E.A. Kearns, S. Magaña, D.V. Lim, R. Fujioka, 2014, “Detection and quantification of microorganisms in recreational and potable water in Hawaii by high-volume ultrafiltration method,” in AWWA Water Quality and Technology Conference, New Orleans, Louisiana, November 16–20, pp 400–408.

Problem and Research Objectives

Problem I: Distribution of microorganisms in beach water and sand is patchy.

It is well established that distribution of microbes in the environment is heterogenous (Whitman and Nevers 2004), and that the detection of a sewage contamination event may be missed when using current water quality monitoring programs that utilize samples of 100 mL. A single 100 mL sample of water or sand may not be representative of the actual water quality and of the associated human health risk at a given site (Whitman and Nevers 2004). Sample volumes larger than 100 mL should be analyzed which would require a concentration technique.

Problem II: Fecal indicator bacteria can originate from multiple sources, and source specific markers may elude detection by conventional methods because marker concentrations are often low.

Reliable information on a contamination source is needed to make meaningful management decisions and to better protect public health in Hawaii. Fecal indicator bacteria can originate not only from humans but from animals and have been isolated from the environment (Byappanahalli et al. 2012a, Byappanahalli et al. 2012b, Hardina and Fujioka 1991, Harwood et al. 2014). Several source specific bacteria and viruses have been identified in the last decade and have been validated by our laboratory for use in water quality monitoring (Harwood et al. 2013, Harwood et al. 2014, Boehm et al. 2013, McQuaig and Noble 2011). They have been tested for sensitivity, specificity and survival in water samples from coastal and inland sites of Oahu. Since the levels of source specfic microorganisms are relatively low compared to indicator bacteria, the detection and quantification of source specific markers is hampered and the ability to concentrate source specific markers from large sample volumes is needed.

Problem III: Monitoring for fecal indicator bacteria may not be sufficient to adequately protect public and environmental health. Monitoring for human pathogens themselves, however, is difficult using conventional methods because their concentrations in 100 mL samples are often below the detection limit.

Direct targeting of human pathogens is important today because the changing environment (climate change and related ocean acidification, storm events) will alter the dynamics of microbial communities including those consisting of environmental and sewage-borne pathogens. The direct surveillance of pathogens is currently not possible for several reasons, one of which is that human pathogens are usually in low amounts in the environment. The ability to concentrate large volume samples is needed.

Solution: The Portable Multi-use Automated Concentration System (PMACS) is a hollow fiber based dead-end ultrafiltration device developed and validated at Dr. Daniel Lim's laboratory at the University of Southern Florida (USF). This system allows analyses of sample volumes 1,000× larger (100 L) than sample volumes analyzed by traditional filtration techniques (100 mL). It offers two major advantages: 1) PMACS enables detection of low level microbial targets such as source specific markers and human pathogens, and 2) PMACS reduces sample variability in long-term monitoring programs because the analysis of a large volume sample is more representative of the site than analysis of a single sample of 100 mL.

This filtration system has been used by the USF group for a variety of microorganisms but needs further evaluation under conditions specific for Hawaii.

Project Goal: This project will evaluate the ability of PMACS to concentrate microbial indicator bacteria and source specific microorganisms as well as human pathogens from large volume water samples collected on Oahu.

Research Objectives

1) Conduct laboratory experiments to recover heterotrophic plate count bacteria (HPC), total coliform (TC), *E. coli* (ECOLI), enterococci (ENT), *Clostridium perfringens* (CPERF), and the molecular markers for human *Bacteroides* (HBAC) and human polyomaviruses (HPyV) using PMACS by spiking sewage into a large volume of drinking water. The PMACS results will be compared to those obtained by conventional filtration methods using 100 mL grab samples.
2) Compare ultrafiltration (100 L samples) and standard filtration techniques (100 mL grab samples) on field samples collected from drinking water systems, Manoa Stream, and coastal beaches of Oahu.

Methodology

Operation of the Ultrafiltration Unit, PMACS

Sample water is passed through the unit at a flow rate of 3.0–3.8 L/min. The water passes through cartridges with a pore size of 30 kDa that traps the microbiological material. If the unit is used "in the field", the cartridges are removed, stored in the cold, and transported to the laboratory. The cartridges are eluted with phosphate buffer (0.1 M sodium phosphate with 0.01% sodium polyphosphate) using the instrument's default recovery protocol. Roughly 350 to 375 mL of retentate is recovered from the cartridges and can then be assayed for particular bacteria, viruses, or markers.

Spiking Experiment

104 L of drinking water collected from the laboratory sink faucet was mixed with 100 mL of raw sewage from Honouliuli Wastewater Treatment Plant (WWTP). 100 L were passed through the PMACS and the remainder was used as a grab sample.

Environmental Samples

During the first round of collection, which occurred February 2–5, 2014, 100 L of water were collected and concentrated from two drinking water sources and four beach sites. Single 1 L grab samples were also taken at the same time. The cartridges from the unit and the grab samples were stored in the cold and transported to the laboratory to be processed.

- Drinking Water Sources:
  Board of Water Supply building (630 S. Beretania St., Honolulu), Palolo tunnel pump station (before chlorination and distribution).

- Beach Sites for Round 1:
  Ala Moana Beach (Diamond Head side), Ala Moana Beach middle, mouth of Ala Wai Canal (next to Magic Island), San Souci Beach.

During the second round of collection, March 24–28, 2014, 100 L of water was concentrated from three beach sites and three 1 L grab samples were collected at each of the three sites (9 grab samples) to explore the variability associated with the size of a conventional grab sample. The cartridges from the PMACS and the grab samples were stored in the cold and transported to the laboratory to be processed.

- Beach Sites for Round 2:
  Ala Moana Beach (Diamond Head side), Ala Moana Beach middle, mouth of Ala Wai Canal (next to Magic Island).

All retentate and grab samples, were serially diluted as appropriate in Phosphate Buffered Dilution Water (USEPA 2002) and analyzed for heterotrophic plate count (HPC), total coliforms (TC), *E. coli* (ECOLI), enterococci (ENT), *C. perfringens* (CPERF), F+ specific coliphage (PHAGE), human Bacteroidales (HBAC) and human polyomaviruses (HPyV). HPC was determined using 100 µl sample portions with the Simplate binary detection technology by BioControl Systems (Bellevue, WA). TC, ECOLI and ENT concentrations were determined using Colilert-18 and Enterolert tests by IDEXX Laboratories, Inc. (Westbrook, ME). PHAGE concentrations were determined using 5 mL sample portions and a single agar layer procedure modified from Method 1602 (USEPA 2001).

For the molecular tests HBAC and HPyV the pH of the water samples (both grab samples and retentates recovered from PMACS) was adjusted to 3.5 using 6N HCl and 300 mL of the grab samples or 75 mL of the ultrafiltration retentate were filtered through a 0.45 µm membrane filter (GN-6 Metricel, Pall Life Sciences, Ann Arbor, MI). DNA was extracted from the filters using the PowerSoil® DNA extraction kit (MO BIO Laboratories, Inc., Carlsbad, CA) according to the manufacturer's protocol, except that bead beating was performed for two minutes on the Mini-BeadBeater-8 (BioSpec Products, Bartlesville, OK). The final elution volume for the DNA extraction kit was 100 µl. HBAC and HPyV concentrations were determined by qPCR using primers and probes specified in Haugland et al. (Haugland et al. 2010) and McQuaig et al. (McQuaig et al. 2009) on a CFX96 real-time System (Bio-Rad Laboratories, Inc., Hercules, CA) using SsoAdvanced (Bio-Rad Laboratories, Inc., Hercules, CA) chemistry with 500 nM primer and 80 nM probe concentrations. Trace quantities of salmon sperm DNA were seeded into the PCR reactions to identify samples containing inhibitors as in Haugland et al. (2005). Samples that were delayed by more than three PCR cycles were considered inhibited and further diluted 1:10. Linearized plasmids containing primer and probe specific DNA regions were quantified using Qubit 2.0 fluorometer (Life Technologies, Inc., Grand Island, NY) and used as a quantification standard for qPCR reactions.

Principal Findings and Significance

Sewage Spiking Experiments

The first set of tests were performed by spiking 104 L of tap water with 100 mL raw sewage from Honouliuli WWTP. Results obtained with the ultrafiltration unit were positive for

all microbiological tests performed, but the standard membrane filtration technique using 100 mL did not detect ENT, PHAGE, and HPyV. Concentrations of microorganisms determined by both sampling techniques were comparable. These tests provided preliminary evidence that the ultrafiltration method is a sensitive method to detect and quantify a variety of microorganisms.

Recreational Water Samples

Based on the eight microbiological tests conducted on seven samples collected at four beach sites, the ultrafiltration system was more effective in recovering different groups of microorganism than grab samples (Table 1). 73.2% of the tests conducted on samples collected by the ultrafiltration device were positive (41 positive test out of 56 tests) and 58.9% of microbiological tests conducted on the grab samples (33 positive tests out of 56 tests). While HPC and TC were constistently recovered by both methods, PHAGE and HPyV were only recovered using the ultrafiltration device.

Table 1. Recovery of microorganisms from beach water samples during Rounds 1 and 2. Number of positive samples over total number of samples taken as indicated.

Group	Ultrafiltration Sample (No. positive/Total)	Grab Sample (No. positive/Total)
HPC	7/7	7/7
TC	7/7	7/7
ECOLI	7/7	6/7
ENT	7/7	4/7
CPERF	7/7	7/7
PHAGE	1/7	0/7
HBAC	3/7	2/7
HPyV	2/7	0/7

There was a significant positive correlation between the measurements obtained from grab samples and measurements obtained using the ultrafiltration device when back calculated to a 100 mL sample volume (Figure 1) which indicates a good agreement between the concentration estimates obtained by the two methods.

Concentration measurements obtained by using the ultrafiltration device tended to be lower than measurements obtained by direct analyses of grab samples (Figure 2) because the elution of materials from the hollow fiber filters is never 100% efficient. While this needs to be considered when interpreting quantitative data, the ultrafiltration device recovered targets that eluded detection when grab samples from the same site were analyzed. Errors associated with multiple grab samples were often several orders of magnitude different indicating the uneven distribution of microorganisms in small volumes. Major measurement error was associated with the HPC counts. This could probably be attributed to the small sample portion (100 µl) analyzed by the Simplate method, further confirming the patchy distribution of microorganisms.

Samples concentrated using the ultrafiltration method can contain elements which interfere with microbiological tests. For example, highly turbid material can cause problems with backgrounds or clogging when a membrane filtration method is used or PCR inhibitors can interfere with molecular tests. Membrane filtration issues can sometimes be overcome by

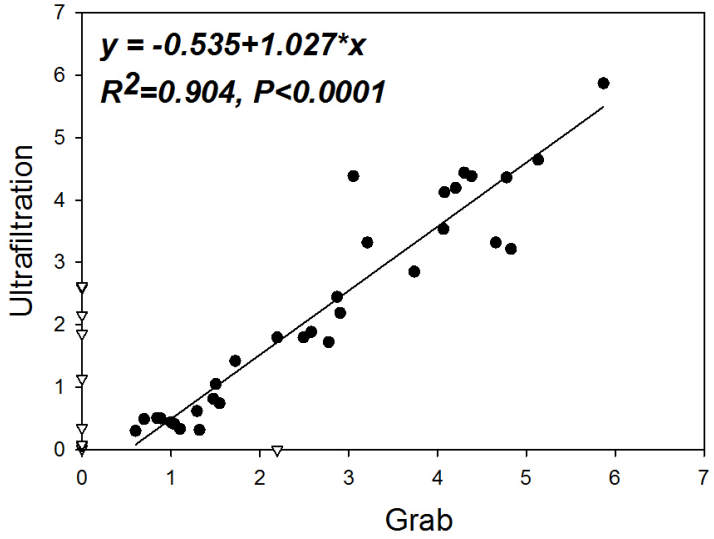

Figure 1. The correlation between the microbiological results obtained from the 1 L (Round 1) grab samples and those obtained using the ultrafiltration device (PMACS). Triangles indicate samples that were not used for analyses as concentration measurements were not available by both methods.

using alternative MPN based techniques while the material used for molecular tests can be purified using commercial kits. We did encounter issues with PCR inhibitors when the retentate eluted from the hollow fiber filters was adjusted to pH 3.5 and further concentrated using the conventional membrane filtration technique. A 1:10 dilution of the DNA material extracted from the filter alleviated the effect of inhibitory compounds. Samples analyzed in parallel from the same concentrate without pH adjustment were not compromised by PCR inhibitors. Because Leskinen et al. (2010) did not detect inhibitors after pH adjustment using a urea-lysine buffer, the inhibition was likely related to the sodium phosphate based elution buffer used in this study which required generous amounts of HCl for adjustment.

Sample volumes tested within this study did not exceed 100 L, but large volumes of ground and coastal waters could potentially be concentrated if needed using this device. During this study the flow rate through the unit varied between 3.0–3.8 L /min, and did not change substantially during the filtration processes. This indicates that larger volumes of ground and coastal waters could have been concentrated. In this regard, ~500 L of groundwater samples have been concentrated using this ultrafiltration device without compromising the filter cartridges in an earlier study conducted in Florida (Dr. E. Kearns, personal communication).

The Hawaii state water quality standard (single sample standard threshold value of 130 CFU of enterococci per 100 mL water sample [HAR 2014]) was exceeded in a single sample collected at the mouth of the Ala Wai Canal which is listed as one of the State's impaired water bodies by the EPA, has been posted by HIDOH, and is not used for swimming by the public. It should also be noted that human polyomaviruses were detected in a single water sample that complied with water quality standards. This indicates that human pathogens, such as human polymaviruses can be detected in water samples that comply with standards. It should be noted though, that this detection was based on a molecular assay and does not necessarily indicate presence of infective viral particles. Despite the detection of human polyomaviruses in a single sample by molecular assay, collectively our results indicate good microbial water quality for Hawaii beaches.

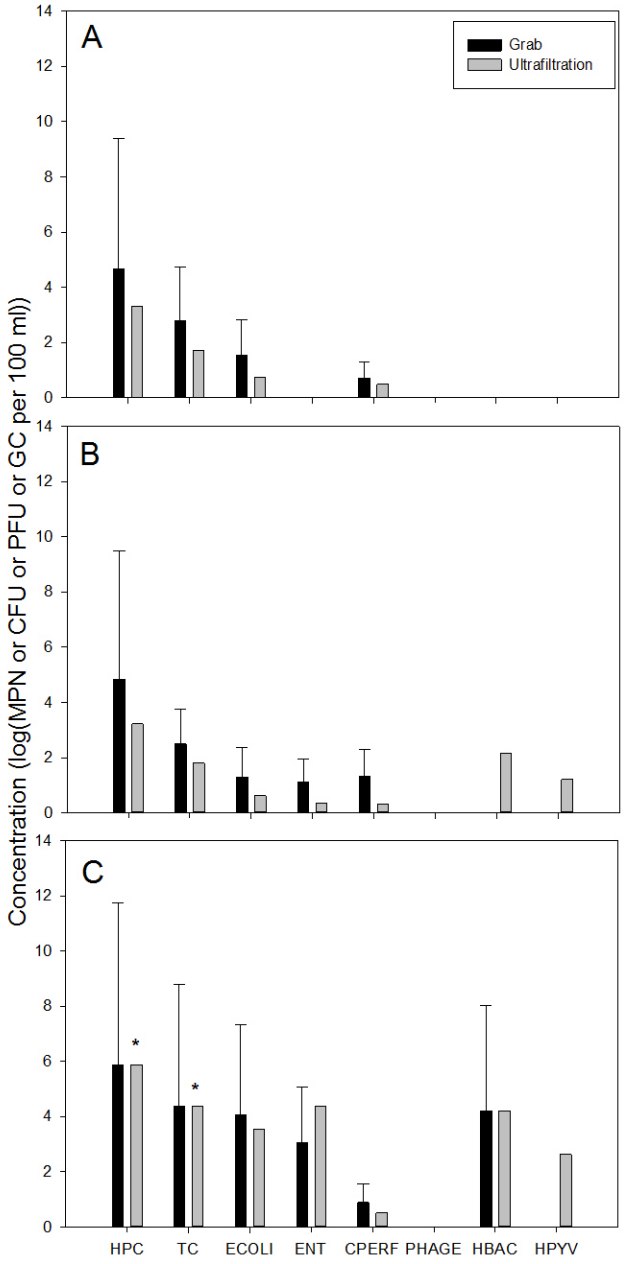

Figure 2. Recovery of microorganisms at three beach sites: A. Ala Moana Beach (Diamond Head side), B. Ala Moana Beach (middle), and C. Ala Wai Canal at Magic Island's boat ramp using triplicate grab samples and an ultrafiltration method (Round 2 samples). Asterisks indicate samples that exceeded the maximum detection limit of the assay based on the dilution series used. HPC, TC, ECOLI, and ENT were measured as most probable number (MPN), CPERF as colony forming units (CFU), PHAGE as placque forming units (PFU), and HBAC and HPYV as gene copies (GC) per 100 mL.

Source Water Samples

Source water samples collected at two sites contained no cultivable cells of *E. coli*. From the 100 L sample volume analyzed using the ultrafiltration device, we were able to estimate that *E. coli* concentrations were < 0.001 MPN per 100 mL. Heterotrophic bacteria were detected in all groundwater samples up to concentrations of 9,000 MPN per 100 mL.

Total coliform concentrations varied from <1 to 5 MPN per 100 mL. All other microbiological tests were negative using both collection methods. Our findings indicated excellent microbial water quality at both City source water sites.

Training and Workshop

In collaboration with Dr. Daniel Lim's laboratory at the University of South Florida (USF), the project was kick-started with a five day workshop (Figure 3). Dr. Kirs, as well as members of the Hawaii State Department of Health (HIDOH) and City and County of Honolulu Laboratory Services, were trained to use the PMACS for sample collection. PMACS was also introduced to a wider audience during the WRRC seminar series (February 5, 2014). The workshop and the seminar generated strong interest in this methodology, and we have received additional funds from HIDOH and a private sponsor for related research activities using PMACS.

There is a follow up workshop planned for June 1–5, 2015 and we will continue to collaborate with HIDOH and USF.

Figure 3. Training session during the workshop. Members of Dr. Daniel Lim's laboratory are demonstrating how to collect and recover samples using PMACS.

Ongoing Work

Our analyses indicate that this type of ultrafiltration method is highly sensitive for the detection and quantification of a wide array of microbial targets and provides a more comprehensive characterization of microbial water quality. Therefore, we would like to encourage the utilization of ultrafiltration devices in routine water quality monitoring programs.

This research was conducted using the PMACS device provided by Dr. Daniel Lim's laboratory at USF. We are expecting to complete the purchase of the PMACS by May 2015. Field testing of the instrument will be ongoing. Additional training will be provided to the Hawaii Department of Health. A summer intern (Ms. Bruna Chieza Madeira, New Mexico State University), and a post-doctoral researcher (Roberto Augusto Caffaro Filho, Federal University of Alagoas, Brazil) will be joining this project from May–August 2015.

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Estimating Evapotranspiration Over Native Wet Montane Cloud Forests in Hawai'i and Evaluating the Impact of Climate Change on it

Basic Information

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Problem and Research Objectives

Sensible and latent heat fluxes are the key variables in energy and water vapor exchange between the land surface and the atmosphere. Latent heat flux is the coupling link between the surface water, energy, and carbon exchanges with the atmosphere. Several techniques (e.g., lysimeters, eddy covariance systems, Bowen ratio methods, and large-aperture scintillometers) have been used to measure surface heat fluxes (Liu et al., 2011, 2013). However, in situ measurements of heat fluxes are costly and are therefore distributed sparsely, and cover only limited time periods. Consequently, a number of models have been developed to estimate surface heat fluxes from remotely sensed land surface temperature (LST) observations.

LST lies at the heart of the surface energy balance (SEB) equation. All components of the SEB equation (i.e., sensible, latent, and ground heat fluxes as well as net radiation) are related to LST. Recently, Bateni and Entekhabi (2012a) showed that LST observations contain implicit information on the partitioning of available energy among the SEB components. LST observations have been utilized in three main groups of studies to estimate surface heat fluxes. The first group of studies is diagnostic. These studies use LST to solve the SEB equation and retrieve surface energy fluxes (Norman et al., 1995; Anderson et al., 1997; Bastiaanssen et al., 1998a, 1998b; Su, 2002; Liu et al., 2007; Jia et al., 2009; Ma et al., 2012). The ground heat flux is usually taken as an empirical fraction of the net radiation. Additionally, surface heat fluxes can be retrieved only for instances in which remotely sensed LSTs are available. The second group is known as triangle approaches. These studies attempt to estimate the surface evaporation using empirical relationships between LST and vegetation indices such as the normalized difference vegetation index and leaf area index (LAI) (Jiang and Islam, 2001, 2003; Nishida et al., 2003; Wang et al., 2006; Tang et al., 2010; Sun et al., 2013). These methods need to define the dry and wet edges of the triangle space, which is site specific.

The third group of studies estimates the surface heat fluxes by assimilating sequences of LST measurements within a variational data assimilation (VDA) framework using the parsimonious force-restore equation as a constraint (Castelli et al., 1999; Boni et al., 2001; Caparrini et al., 2003, 2004a, 2004b; Crow and Kustas, 2005; Qin et al., 2007; Sini et al., 2008). In contrast to the diagnostic and triangle approaches, this group of methods does not require any empirical or site-specific relationships and can provide temporally continuous surface heat flux estimates from discrete spaceborne LST observations.

The VDA utilizes combined-source (CS) and dual-source (DS) schemes to simulate interaction between the land surface and the overlying air and to retrieve surface heat fluxes. The CS scheme does not distinguish the difference between soil and canopy temperatures and treats LST as the effective temperature of a mixed soil-vegetation medium. In contrast, the DS scheme accounts for the difference between soil and canopy temperatures and considers the interactions of the soil and canopy with the overlying atmosphere separately.

Bateni and Liang (2012) and Bateni et al. (2013a, 2013b) significantly advanced the CS and DS VDA approaches by using the full heat diffusion equation as a physical constraint instead of the simple force-restore equation. However, the CS and DS VDA approaches by Bateni and Liang (2012) and Bateni et al. (2013a, 2013b) have been tested so far at only two humid sites with grassland vegetation cover (i.e., the First International Experiment and the Southern Great Plains sites). In this study, the performance of the recently augmented CS and DS VDA frameworks is assessed in detail using surface heat fluxes collected at six FluxNet sites with different vegetation covers (grassland, cropland, and forest) and climate conditions. These

sites are chosen because they sample different climatic and vegetative conditions in an effort to evaluate the robustness of the VDA schemes in various hydrological environments.

Sequences of daytime LST observations have various diurnal amplitudes depending on the available energy and the relative efficiency of SEB components (Bateni and Entekhabi, 2012a). Hence, an accurate characterization of the LST diurnal cycle is of vital importance for the reliable performance of the VDA methods. In this study, LST data from Geostationary Operational Environmental Satellites (GOES) are assimilated in the CS and DS VDA schemes to estimate surface heat fluxes. GOES can accurately characterize the LST diurnal cycle by providing LST data every 30 min and thus can significantly advance the robustness of the VDA framework. GOES LST can be accurately retrieved (Sun et al., 2004) and proved to be a significant data set for improving turbulent flux estimates of the land surface model (Xu et al., 2011).

Methodology

Heat Diffusion Equation

The soil temperature at depth z and time t, $T(z,t)$, is given by the heat diffusion equation, which is given by

$$C\frac{\partial T(z,t)}{\partial t} = P\frac{\partial T^2(z,t)}{\partial z^2} \tag{1}$$

where C and P are, respectively, the soil volumetric heat capacity (J m^{-3} K^{-1}) and thermal conductivity ($Wm^{-1}K^{-1}$). For simplicity, $T(z = 0,t)$ is indicated by $T(t)$.

The boundary conditions at the top and bottom of the soil column are required to solve the heat diffusion equation. The boundary condition at the top of the soil column, $T(z = 0,t)$, is retrieved from the surface boundary forcing equation $P\, dT(z = 0,t)/dz = G(t)$ (where $G(t)$ is the ground heat flux at time t) (Bateni et al., 2013a). At the bottom boundary, a Neumann boundary condition is implemented as

$$\frac{\partial T(l,t)}{\partial t} = 0 \tag{2}$$

where l is the depth of the bottom boundary condition, which is set to 0.5 m (Hu and Islam, 1995; Bateni and Liang, 2012; Bateni et al., 2013a). The heat diffusion equation is solved using an implicit finite difference scheme. The detailed information on discretization of the heat diffusion equation and its numerical implementation can be found in Bateni et al. (2012).

Surface Energy Balance (SEB)

The CS SEB scheme considers the soil and vegetation as a single source and follows Bateni et al. (2013a). For the CS approach, the land surface energy balance equation can be written as

$$G = R_N - H - LE \tag{3}$$

where G is the ground heat flux (Wm^{-2}), H and LE are the sensible and latent heat fluxes (Wm^{-2}), and R_N is the net radiation (Wm^{-2}) that is obtained according to Bateni et al. (2013a).

The sensible heat flux can be obtained with the LST (T) generated by the heat diffusion equation as follows:

$$H = \rho\, c_p C_H\, \mathrm{U}(T - T_A) \tag{4}$$

where ρ is the air density (kg m^{-3}), c_p is the heat capacity of air (1012 J kg^{-1} K^{-1}), U and T_A are, respectively, the wind speed (m s^{-1}) and air temperature (K) at a reference height, and C_H is the bulk heat transfer coefficient (-). The bulk heat transfer coefficient (C_H) can be written as the product of the neutral bulk heat transfer coefficient (C_{HN}) and a correction function for atmospheric stability, $f(Ri)$ (i.e., $C_H = C_{HN}\, f(Ri)$, where Ri is the Richardson number). C_{HN} can be related to roughness length scales for heat and momentum (Liu et al., 2007; Zhang et al., 2010), which is mainly a function of vegetation phenology and is assumed to vary on a monthly temporal scale (McNaughton and Van den Hurk, 1995; Jensen and Hummelshøj, 1995; Qualls and Brutsaert, 1996; Crow and Kustas, 2005; Bateni et al., 2013b). It scales the sum of turbulent heat fluxes ($H + LE$) and constitutes the first unknown parameter of the CS scheme. Following Crow and Kustas (2005), Sini et al. (2008), Bateni and Liang (2012), and Bateni and Entekhabi (2012b), the atmospheric correction function (f) proposed by Caparrini et al. (2003) is used herein.

The second unknown of the CS scheme is evaporative fraction (EF), which scales partitioning between the turbulent heat fluxes and is given by

$$EF = \frac{LE}{H+LE} \tag{5}$$

The DS SEB scheme developed by Bateni and Liang (2012) is used in this study. The DS can model interaction within the soil-canopy-atmosphere system (Kustas et al., 1996; Bateni and Liang, 2012). In the DS SEB model, the net radiation absorbed by the canopy (R_{NC}) is partitioned between the sensible (H_C) and latent (LE_C) heat fluxes for the canopy ($R_{NC} = H_C + LE_C$, the subscript "C" refers to the vegetation canopy). The ground heat flux (G) can be calculated as the residual of the surface energy balance for soil (Bateni and Liang, 2012).

The sensible heat fluxes for the canopy (H_C) and soil (H_S) can be estimated via (Bateni and Liang, 2012)

$$H_c = \rho\, c_p C_{HC}\, U_W (T_C - T_W) \tag{6a}$$

$$H_s = \rho\, c_p C_{HS}\, \mathrm{U}_W (T_S - T_W) \tag{6b}$$

where U_W and T_W are, respectively, the wind speed and air temperature at a reference height within the canopy, T_C and T_S are the canopy and soil temperatures, and C_{HC} and C_{HS} are the bulk heat transfer coefficients from leaves and soil to air within the canopy (-). T_S is estimated with the heat diffusion equation (equation (1)). Equations for the estimation of T_C and T_W can be found in Bateni and Liang (2012). C_{HC} and C_{HS} are related to C_{HN} to decrease the number of unknown parameters of the DS scheme. For detailed information, the reader is referred to Bateni and Liang (2012) and Bateni et al. (2013b).

The total sensible heat flux (H) can be estimated via

$$H = \rho\, c_p C_H\, U \quad (T_W - T_A) \tag{7}$$

Similar to the CS SEB scheme, C_H is related to C_{HN} via $C_H = C_{HN}\, f(Ri)$. The total sensible heat flux (H) is also given by the weighted average of sensible heat flux from the canopy and soil:

$$H = f_c H_c + (1 - f_c)\, H_s \tag{8}$$

where f_c is the vegetation cover fraction. The evaporative fractions for the soil and canopy (EF_S and EF_C) are the other unknown parameters of the DS scheme and are given by

$$EF_c = \frac{LE_c}{H_c + LE_c} \tag{9a}$$

$$EF_s = \frac{LE_s}{H_s + LE_s} \tag{9b}$$

C_{HN}, EF_S and EF_C are the three unknown parameters of the DS SEB scheme that are estimated via a VDA framework.

In the DS SEB scheme, the effective LST is calculated through a composite of the soil and canopy temperatures are follows:

$$T = [f_c T_c^4 + (1 - f_c) T_s^4]^{0.25} \tag{10}$$

Adjoint State Formulation

As mentioned in the previous section, C_{HN} and EF constitute the unknown parameters of the CS SEB scheme that should be estimated by the VDA approach. In the DS SEB model, three unknown parameters (i.e., C_{HN}, EF_C and EF_S) must be estimated. C_{HN} varies on a monthly time scale (i.e., the scale of vegetation phenology) and thus one C_{HN} value is retrieved in each monthly modeling period (Caparrini et al., 2003, 2004a, b; Crow and Kustas, 2005; Bateni and Liang, 2012; Bateni and Entekhabi, 2012b; Bateni et al., 2013a, b). EF is self-preserved during daytime hours (i.e., 09:00–16:00 LT), but it can vary from day to day (Gentine et al., 2007).

A cost function (J) is defined to retrieve the unknown parameters of the CS scheme (i.e., C_{HN} and EF) by minimizing the difference between the LST observations (from GOES) and estimates (from the heat diffusion equation). The cost function for the CS model can be written as

$$\begin{aligned} &J(T, R, EF, \lambda) = \\ &\sum_{i=1}^{N} \int_{t_0}^{t_1} [T_{OBS,i}(t) - T_i(t)]^T K_T^{-1} [T_{OBS,i}(t) - T_i(t)] dt \\ &+ (R - R')^T K_R^{-1} (R - R') + \sum_{i=1}^{N} (EF_i - EF_i')^T K_{EF}^{-1} (EF_i - EF_i') \\ &+ 2 \sum_{i=1}^{N} \int_{t_0}^{t_1} \int_0^l \lambda_i(z,t) [\frac{\partial T_i(z,t)}{\partial t} - D \frac{\partial^2 T_i(z,t)}{\partial z^2}] dz dt \end{aligned} \tag{11}$$

The first term on the right-hand side of Eq. (11) measures the difference between the GOES-measured LST (T_{OBS}) and the predicted LST (T). C_{HN} is transformed to R via C_{HN} = exp(R) to make it strictly positive and meaningful. The second and third terms measure the difference between the parameter estimates (R and EF) and their prior values (R' and EF'). As previously mentioned, C_{HN} is hypothesized to be constant over the entire monthly assimilation period (N = 30 days), and EF is postulated to be invariant over each day during the assimilation window (i.e., from t_0 = 9:00 to t_1 = 16:00 LT). The last term is the heat diffusion equation, which is adjoined to the model (as a physical constraint) via the Lagrange multiplier, λ. $D = P/C$ is the heat diffusion coefficient. K_T^{-1}, K_R^{-1}, and K_{EF}^{-1} are numerical constant parameters that weigh each term in the objective function and control its rate of convergence. Following Bateni et al. (2013a), K_T^{-1}, K_R^{-1}, and K_{EF}^{-1} are set to 0.01 K^{-2}, 1000, and 1000, respectively.

The optimal values for C_{HN} and EF are found by minimizing the cost function. To minimize the cost function, its first variation should be set to zero ($\Delta J = 0$) (Bennett, 1992). Setting ΔJ to zero leads to a number of Euler-Lagrange equations that should be solved simultaneously through an iterative loop to obtain optimal values of C_{HN} and EF. The Euler-Lagrange equations for the CS VDA scheme can be found in Bateni et al. (2013a).

Similarly, C_{HN}, EF_S and EF_C are estimated by minimizing the difference between the GOES LST and the effective LST estimates (Eq. 10). The cost function for the DS model is defined as,

$$
\begin{aligned}
&J(T,R,EF_S,EF_C,\lambda) = \\
&\sum_{i=1}^{N}\int_{t_0}^{t_1}[T_{OBS,i}(t)-T_i(t)]^T K_T^{-1}[T_{OBS,i}(t)-T_i(t)]dt \\
&+(R-R')^T K_R^{-1}(R-R') + \sum_{i=1}^{N}(EF_{S,i}-EF'_{S,i})^T K_{EF_S}^{-1}(EF_{S,i}-EF'_{S,i}) \\
&+\sum_{i=1}^{N}(EF_{C,i}-EF'_{C,i})^T K_{EF_C}^{-1}(EF_{C,i}-EF'_{C,i}) \\
&+2\sum_{i=1}^{N}\int_{t0}^{t1}\int_0^l \lambda_i(z,t)[\frac{\partial T_{S,i}(z,t)}{\partial t} - D\frac{\partial T_{S,i}^2(z,t)}{\partial z^2}]dz\,dt
\end{aligned}
\tag{12}
$$

where the third and fourth terms on the right-hand side of Eq. (12) measures the difference between the soil and canopy evaporative fraction estimates and their prior values, respectively. $K_T^{-1}, K_R^{-1}, K_{EF_S}^{-1}$, and $K_{EF_C}^{-1}$ are respectively set to 0.01 K^{-2}, 1000, 1000, and 1000 based on Bateni and Liang (2012).

In the DS VDA scheme, the optimal values for C_{HN}, EF_S and EF_C are found by minimizing the cost function (Eq. 12). Setting ΔJ to zero yields a number of Euler-Lagrange equations as follows:

$$
\frac{\partial \lambda}{\partial t} + D\frac{\partial^2 \lambda}{\partial z^2} = 0 \tag{13a}
$$

$$\lambda(z,t_1)=0 \tag{13b}$$

$$\left.\frac{\partial\lambda}{\partial z}\right|_{z=0}=\frac{K_T^{-1}}{D}(T-T_{OBS})(1-f_C)T_S^3T^{-3}$$
$$+\frac{\lambda(0,t)}{P}[4\varepsilon_s\sigma T_s^3+\frac{\rho c_P e^R f(Ri)U\exp(-a_H\,\mathrm{LAI})}{1-EF_S}](1-f_C) \tag{13c}$$

$$\left.\frac{\partial\lambda}{\partial z}\right|_{z=l}=0 \tag{13d}$$

$$R=R^{'}-\frac{1}{CK_R^{-1}}\sum_{i=1}^{N}\int_{t0}^{t1}\lambda_i(0,t)[\frac{\rho c_P e^R f(Ri)U\exp(-a_H\,\mathrm{LAI})(T_S-T_W)}{1-EF_{S,i}}](1-f_C)dt$$
$$-\frac{K_T^{-1}}{K_R^{-1}}\sum_{i=1}^{N}\int_{t0}^{t1}(T-T_{OBS})\frac{\rho c_P e^R f(Ri)U\exp(-0.5a_H\,\mathrm{LAI})(T_W AA-BB)}{AA^2}f_C T_C^3T^{-3}dt \tag{14a}$$

$$EF_{S,i}=EF_{S,i}^{'}-\frac{1}{CK_{EF_S}^{-1}}\int_{t0}^{t1}\frac{\lambda(0,t)}{(1-EF_{S,i})^2}\rho c_P e^R f(Ri)U\exp(-a_H\,\mathrm{LAI})(T_S-T_W)(1-f_C)dt \tag{14b}$$

$$EF_{C,i}=EF_{C,i}^{'}-\frac{K_R^{-1}}{K_{EF_C}^{-1}}\int_{t0}^{t1}\frac{4\varepsilon_S\sigma T_A^3BB-[(1-\alpha_C)R_S^{\downarrow}+R_L^{\downarrow}+3\varepsilon_S\sigma T_A^4]AA}{AA^2}f_C T_C^3T^{-3}(T-T_{OBS}) \tag{14c}$$

where $AA=4\varepsilon_S\sigma T_A^3(1-EF_C)+\rho c_P C_{HN}f(Ri)\exp(-0.5a_H LAI)U$
$BB=[(1-\alpha_C)R_S^{\downarrow}+R_L^{\downarrow}+3\varepsilon_S\sigma T_A^4](1-EF_C)+\rho c_P C_{HN}f(Ri)\exp(-0.5a_H LAI)UT_W$, ε_S is the soil emissivity (-), σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and $R_S^{\downarrow}$ and $R_L^{\downarrow}$ are the downward shortwave and longwave radiation (W m^{-2}).

The adjoint model (Eq. [13a]) has to be integrated backward in time using the terminal and boundary conditions (Eqs. [13b], [13c], and [13d]). The unknown parameters of the DS scheme (i.e., R, EF_S, and EF_C) can be estimated via Eqs. (14a), (14b) and (14c). The DS VDA scheme improves estimates of the three unknown parameters iteratively starting from the initial guesses (R', EF_S', and EF_C').

Principal Findings and Significance

Neutral Heat Transfer Coefficient and Evaporative Fraction

As mentioned in the previous section, C_{HN} and EF are the two key unknown parameters in the CS model, and C_{HN}, EF_S and EF_C constitute the three unknown parameters in the DS model. C_{HN} and EF are estimated on monthly and daily timescales, respectively. In the VDA framework,

the accuracy of turbulent heat flux estimates mainly depends on the robust retrieval of these unknown parameters.

The estimated C_{HN} values from the CS and DS schemes for the six experimental sites are shown in Table 1. C_{HN} estimates from the CS and DS models have generally the same order of magnitude and are comparable with each other over different assimilation periods. However, in most cases, the DS C_{HN} values are slightly larger than those of the CS model. The discrepancy between C_{HN} estimates from the CS and DS schemes is due to the difference in the structure of the CS and DS schemes. To understand this distinction better, the C_{HN} estimates from the CS, $(C_{HN})_{CS}$, and DS, $(C_{HN})_{DS}$, schemes are related using Eqs. (4) and (8a):

$$(C_{HN})_{DS} = (C_{HN})_{CS} \frac{T - T_A}{T_W - T_A} \tag{15}$$

The land surface temperature (T) is usually larger than the air temperature within the canopy (T_W) during the assimilation window (i.e., $T>T_W$). Subtracting T_A from both sides of the inequality leads to $(T-T_A)>(T_W-T_A)$. Thus, the C_{HN} estimates from the DS scheme should typically be higher than those from the CS scheme (see Table 1).

Table 1. Summary of the Characteristics Over Six Study Sites

Site	Land Cover	LAI ($m^2 m^{-2}$)	f_C	SM ($m^3 m^{-3}$)	C ($J m^{-3} K^{-1}$)	P ($J m^{-1} K^{-1} s^{-1}$)
Brookings	Grassland	1.6	0.55	0.43	3.04×10^6	1.64
Goodwin	Grassland	1.8	0.59	0.31	2.57×10^6	1.75
Bondville	Cropland	2.7	0.74	0.32	2.58×10^6	1.55
Mead	Cropland	1.8	0.59	0.25	2.58×10^6	1.54
Chestnut	Forest	5.4	0.93	0.19	2.06×10^6	1.53
Missouri	Forest	5.4	0.93	0.30	2.53×10^6	1.70

LAI values over different periods are listed in Table 2 to explore the relationship between C_{HN} estimates and vegetation phenology. The C_{HN} estimates generally increase with LAI values at each site. Remarkably, the C_{HN} estimates from both schemes are higher at sites with larger LAI values (i.e., Chestnut and Missouri) (Table 1), implying that the VDA system can robustly retrieve C_{HN} from sequences of LST observations. This is particularly interesting because no information on vegetation phenology is used in the CS model. Yet, its C_{HN} estimates are larger at sites with denser canopies.

Table 2. Neutral Bulk Heat Transfer Coefficient Estimates from the CS and DS Models

	Day of Year	Brookings	Goodwin	Bondville	Mead	Chestnut	Missouri
CS	151–180	1.0×10^{-2}	1.1×10^{-2}	0.6×10^{-2}	1.7×10^{-2}	8.7×10^{-2}	5.7×10^{-2}
	181–210	1.0×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.9×10^{-2}	10.0×10^{-2}	8.7×10^{-2}
	211–240	1.4×10^{-2}	1.5×10^{-2}	1.1×10^{-2}	2.1×10^{-2}	8.9×10^{-2}	10.9×10^{-2}
DS	151–180	1.3×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	2.3×10^{-2}	8.9×10^{-2}	6.1×10^{-2}
	181–210	1.6×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	2.0×10^{-2}	11.5×10^{-2}	9.8×10^{-2}
	211–240	1.8×10^{-2}	1.6×10^{-2}	1.3×10^{-2}	2.2×10^{-2}	7.9×10^{-2}	11.1×10^{-2}
LAI	151–180	1.2	1.7	1.5	1.4	5.0	5.3
	181–210	1.7	2.0	4.0	2.0	5.8	5.6
	211–240	2.0	1.6	2.5	2.0	5.4	5.4

[a]LAI represents the leaf area index.

Figure 1 shows the time series of the evaporative fraction (*EF*) values estimated from the CS and DS schemes. For comparison, *EF* observations are also shown on the same figure. The estimated *EF* values from the CS and DS models agree well with the observations in terms of both magnitude and day-to-day dynamics. Additionally, the DS model yields *EF* values closer to observations than the CS model. Oscillations in the estimated *EF* values are consistent with land surface wetting and drying events. *EF* values increase sharply when precipitation happens and reduce in drydown periods even though no soil moisture or precipitation data are used in the model. For example, during the drydown period at the Brookings (Julian day 171 to 191), Goodwin (Julian day 191 to 211) and Missouri (Julian day 191 to 221) sites, *EF* estimates decrease significantly.

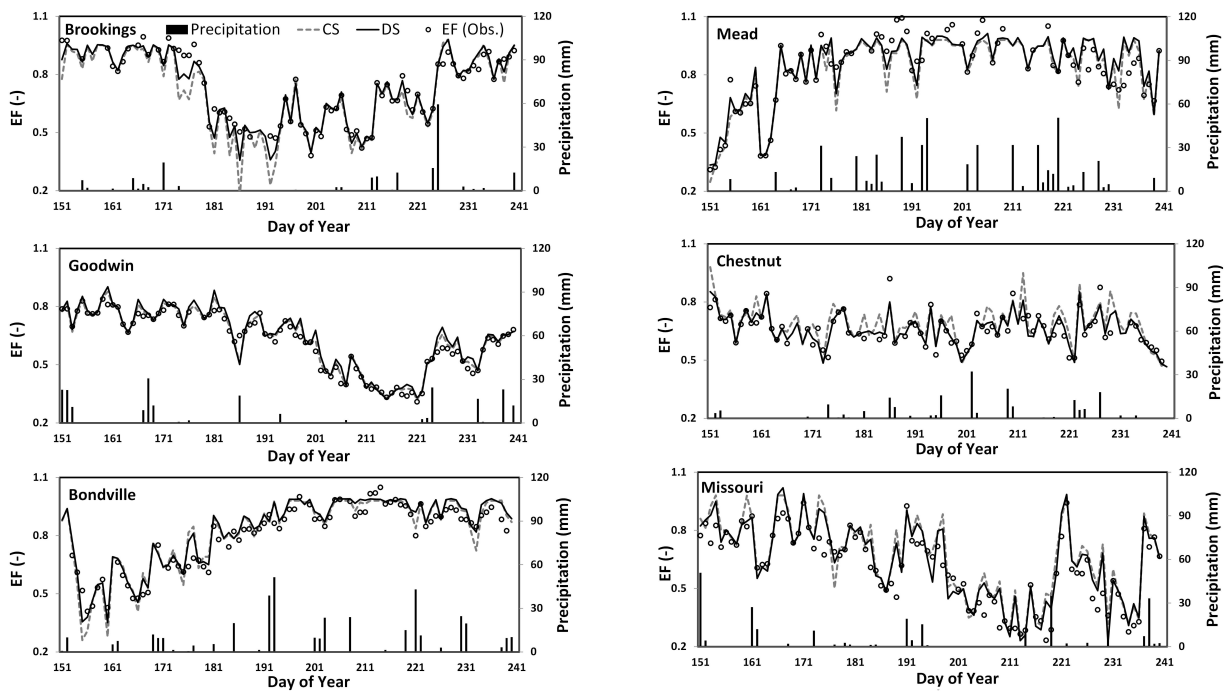

Figure 1. Time series of evaporative fraction (EF) estimates from the CS and DS models.

Sensible and Latent Heat Fluxes

Figure 2 compares the half-hourly turbulent heat flux estimates from the CS and DS models with the corresponding measurements at the Brookings, Goodwin, Bondville, Mead, Chestnut, and Missouri sites. This figure allows us to evaluate the performance of the CS and DS models in different hydrological and vegetative conditions. As shown, the sensible and latent heat fluxes retrieved from both models are in good agreement with the observations and mainly fall around the 1:1 line. Additionally, the DS scheme performs better than the CS scheme. This is because the DS model can represent the physics of the problems more robustly. The misfits between the model estimates and observations are mainly due to the physical assumptions (constant soil thermal conductivity (*P*) and heat capacity (*C*), constant daily *EF*, EF_C, EF_S, constant monthly C_{HN}) in the CS and DS models. Over the Goodwin and Chestnut sites, both the CS and DS schemes tend to overestimate latent heat flux when it is larger than 200 W m^{-2}. This may be due to the undermeasurement of sensible and latent heat fluxes by the Eddy Covariance

(EC) technique, i.e., the so-called "energy imbalance" problem. The energy balance ratio ($EBR = (H+LE)/(R_N-G)$) is 0.78 and 0.75 at the Goodwin and Chestnut sites, respectively, implying that the EC method underestimates the latent heat flux. This leads to a bias greater than 60 W m^{-2} in the *LE* estimates at these two sites.

The bias and root-mean-square error (RMSE) of the turbulent heat flux estimates at the six experimental sites are shown in Figure 2 as well. For sensible heat flux, the six-site-averaged bias and RMSE (shown in parenthesis) from the CS and DS schemes are 7.5 (59.7) and 1.7 (52.5) Wm^{-2}, respectively. For latent heat flux, the six-site-averaged bias (RMSE) is 19.0 (111.1) Wm^{-2} for the CS scheme and 12.7 (96.4) Wm^{-2} for the DS scheme. The low bias and RMSE values imply that the CS and DS schemes can retrieve turbulent heat fluxes accurately.

By treating the soil and the canopy as different sources and accounting for their interaction with the overlying atmosphere in the DS model, the bias (RMSE) of retrieved sensible and latent heat fluxes over the six experimental sites is on average 77% and 33% (12% and 13%) less than that of the CS model. Overall, the statistical metrics in Figure 2 indicate that decomposing the land surface into canopy and soil sources via the DS model improves the estimate of turbulent heat fluxes.

The discrepancies between the results of the CS and DS models are mainly due to the different model structures. The DS model treats the soil and vegetation canopy as dual sources, while the CS model treats them as combined sources. The DS model can characterize the heterogeneity of the land surface and weighs the soil and canopy fluxes via the vegetation cover fraction (f_C) (see Eq. 8b), while the less elaborate CS scheme cannot. The f_C values for the six sites are listed in Table 1. As shown in Figure 2, the largest discrepancy between the CS and DS turbulent heat flux estimates occurs when f_C is approximately 0.5–0.6 (at the Goodwin and Mead sites). When f_C is about 0.5, the land surface heterogeneity is at its peak, and thus the CS model cannot capture the physics of the underlying problem as robustly as the DS model. As a result, the maximum difference is observed between the CS and DS scheme *H* and *LE* estimates (see Table 3). As f_C increases to 0.7 (at the Bondville site), land surface patchiness decreases, and therefore the misfit between the CS and DS model retrievals decreases (Table 3). At an f_C of about 0.9 (at the Chestnut and Missouri sites), land surface patchiness reaches its minimum because the land surface is mainly composed of canopy. Consequently, the CS model can retrieve turbulent heat fluxes almost as accurately as the DS model. Turbulent heat fluxes are mainly controlled by atmospheric factors rather than land surface properties at the Brookings site since it is a wet site. Therefore, even with an f_C value of 0.55 at this site (i.e., high land surface heterogeneity), a small discrepancy is found between the CS and DS model estimates (Table 3). At the Bondville site, f_C illustrates a pronounced seasonal variation and increases from 0.53 (for Julian days 151–180) to 0.86 (for Julian days 181–210). As a result, the discrepancy between turbulent flux estimates from the CS and DS model is higher for Julian days 151–180 compared to Julian days 181–210 (see Table 3).

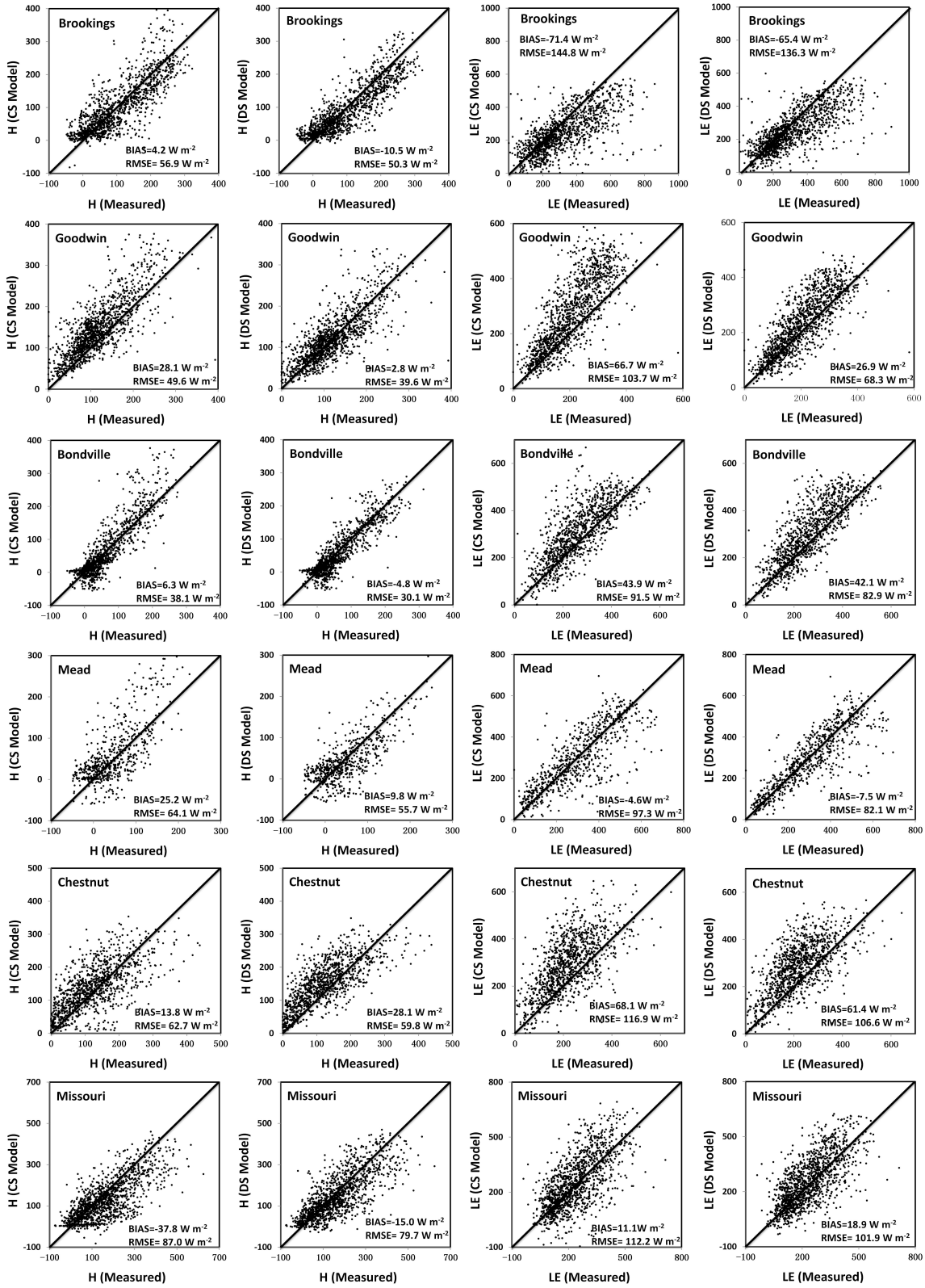

Figure 2. Scatterplots between modeled (CS and DS) and measured (EC data) sensible and latent heat fluxes (*H* and *LE*) in the six sites for Julian days 151–240 in 2006.

Table 3. The Percentage Relative Difference of Turbulent Heat Flux Estimates from the CS and DS Schemes

	Day of Year	Brookings	Goodwin	Bondville	Mead	Chestnut	Missouri
P_H (%)	151–180	−20.4	−23.7	−14.3	−28.4	6.3	9.6
	181–210	−5.2	−15.9	−11.5	−24.5	9.7	14.4
	211–240	−7.7	−15.1	−22.5	−21.1	14.6	14.2
	151–240	−11.1	−18.2	−16.1	−24.7	10.2	12.7
P_{LE} (%)	151–180	3.7	18.7	10.7	11.3	−5.2	−3.1
	181–210	7.7	11.4	0.5	3.5	−2.2	−4.3
	211–240	1.4	12.8	4.6	3.9	−1.1	−2.4
	151–240	4.2	14.3	5.3	6.2	−2.8	−3.3
f_C	151–180	0.45	0.57	0.53	0.50	0.92	0.93
	181–210	0.57	0.63	0.86	0.63	0.94	0.94
	211–240	0.63	0.55	0.71	0.63	0.93	0.93
	151–240	0.55	0.59	0.74	0.59	0.93	0.93

[a] $P_H(\%) = (H(_{DS}) - H(_{CS}))/H(_{CS}) \times 100$ and $P_{LE}(\%) = (LE(_{DS}) - LE(_{CS}))/LE(_{CS}) \times 100$. $H(_{CS})$ and $H(_{DS})$ represent the sensible heat flux estimates from the CS and DS schemes, $LE(_{CS})$ and $LE(_{DS})$ denote the latent heat flux estimates from the CS and DS schemes, and f_C means vegetation cover fraction.

Figure 3 shows the time series of daytime-averaged (0900–600 LT) estimated sensible and latent heat fluxes from the CS and DS models at the six experimental sites. Results from control experiments (i.e., without assimilation of GOES LST) and EC observations are indicated in Figure 3. The CS and DS model estimates are consistent with the observations in terms of both magnitude and day-to-day dynamics, implying that assimilating LST data from GOES can reliably partition the available energy among sensible and latent heat fluxes. However, the turbulent heat flux estimates degrade in wet periods (e.g., Julian days 151–180 at the Brookings site and Julian days 201–215 at the Mead site). At the Brookings and Mead sites (data for Mead shown in parenthesis), the daytime-averaged latent heat flux measurements increase to approximately 700 Wm^{-2} (600 Wm^{-2}) in the corresponding aforementioned wet periods, while the model estimates cannot reach those high values. This happens because the upper bound of *EF* (i.e., EF_S and EF_C) in the CS (DS) model is set to 0.97 to avoid numerical instabilities, while the corresponding *EF* observations are sometimes larger than 1.0 due to negative sensible heat flux measurements (according to Eq. [5], negative sensible heat flux measurements lead to *EF* values larger than 1.0).

As indicated in Figure 3, the estimated *H* and *LE* values from the VDA models are closer to the observations than those of the control experiments. The good agreement between the estimated and observed turbulent heat fluxes illustrates that the VDA model can effectively use implicit information in the LST observations to constrain the unknowns of the CS and DS schemes. In contrast, the control experiments perform poorly since there is no constraint by the LST observations.

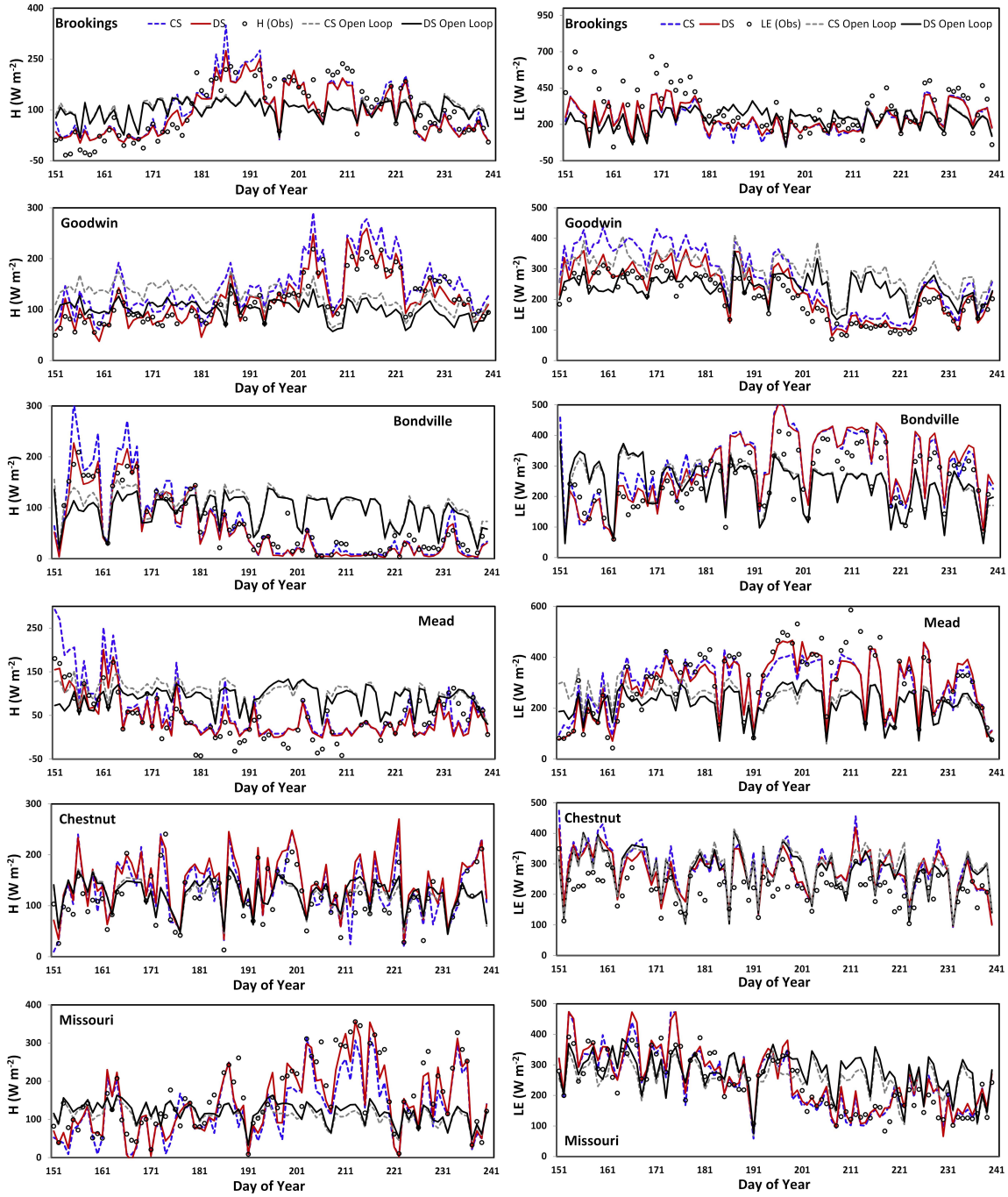

Figure 3. Time series of daytime-averaged sensible and latent heat flux (*H* and *LE*) estimates in the six experimental sites from the CS scheme with (blue dashed lines) and without (grey dashed lines) assimilation of GOES LST. Corresponding estimates from the DS scheme with (red solid lines) and without (black solid lines) assimilation of GOES LST. Observations are shown by open circles.

Figure 4 shows the mean diurnal cycle of observed and estimated turbulent heat fluxes from the CS and DS models at the six experimental sites. As indicated, the diurnal variations of retrieved turbulent heat fluxes from both models agree well with those of observations in terms of magnitude and phase. A large discrepancy between the CS and DS model diurnal cycles is found at the Goodwin ($f_C = 0.59$) and Mead ($f_C = 0.59$) sites, which have high land surface

heterogeneity. In contrast, at sites in which the land surface tends to be more homogeneous (e.g., Bondville, Chestnut, and Missouri, with f_C of 0.74, 0.93, and 0.93, respectively), the diurnal cycle retrievals from the CS and DS scheme are close. At the Chestnut site, the CS and DS models overestimate both the sensible and latent heat fluxes. This is mainly because turbulent heat flux measurements from the EC system at the Chestnut site may contain errors and suffer from the "energy imbalance" problem. Overall, the misfit between the observed and estimated diurnal cycles is due to a number of reasons, including the assumptions of constant daily evaporative fraction and constant monthly neutral bulk heat transfer coefficient and the use of constant soil thermal properties over the modeling period.

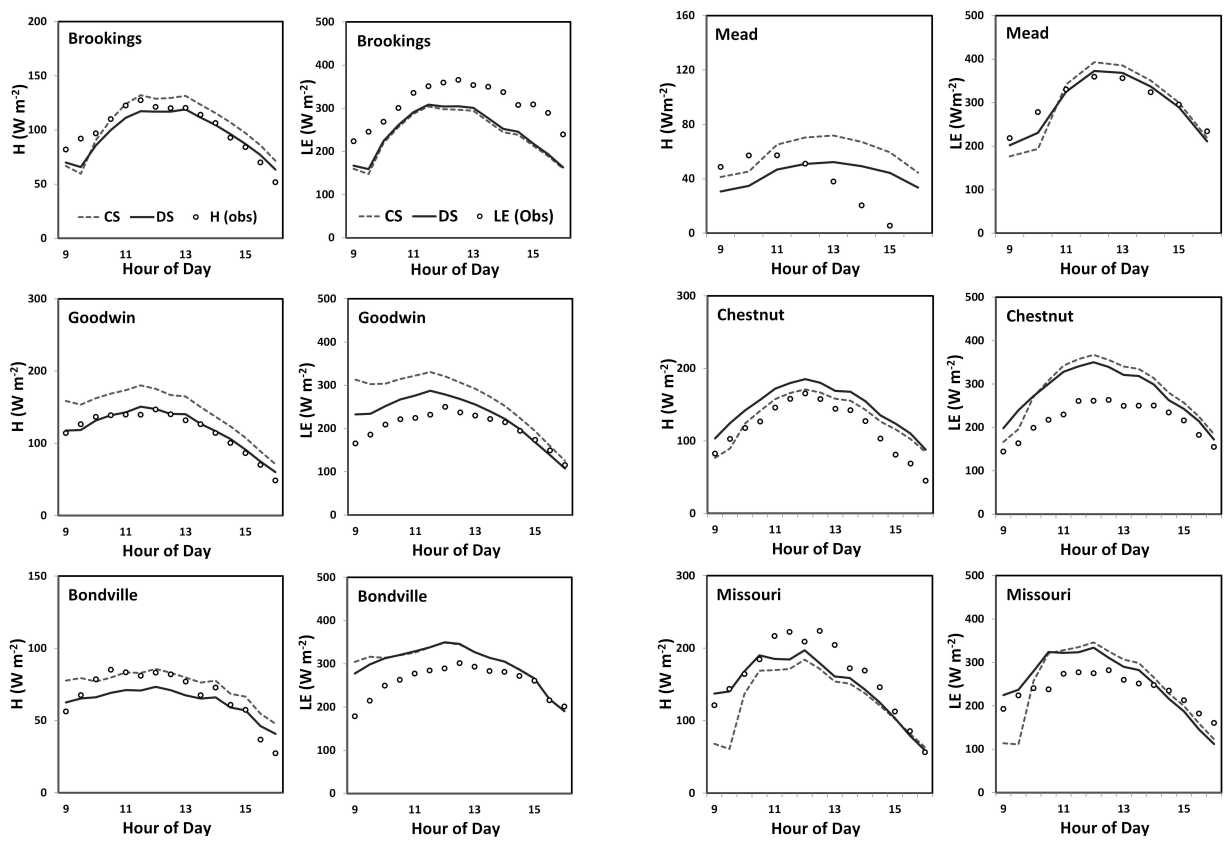

Figure 4. Mean diurnal cycle of turbulent heat flux estimates from the CS and DS models along with the observations in the six experimental sites (H and LE mean sensible and latent heat fluxes).

Figure 5 shows the relationship between RMSE of turbulent heat flux estimates and its soil moisture and vegetation cover fraction, at each of the six explored sites. Each circle corresponds to a site and its size represents the RMSE of flux estimates at the site (larger circles illustrate higher RMSE values). As indicated, the CS and DS models perform better at dry and/or sparsely vegetated sites than at wet and/or densely vegetated sites. Similarly, the results in Figure 2 indicate that the CS and DS schemes yield larger biases and RMSE values (less accurate turbulent heat fluxes) over densely vegetated/wet sites than over lightly vegetated/dry sites. For example, the bias and RMSE of turbulent heat flux estimates at the Chestnut and Missouri sites with denser vegetation cover (i.e., higher LAI value) are larger than those at the Goodwin, Bondville, and Mead sites with lower canopy cover. Additionally, at the Brookings site, which

has higher soil moisture, the turbulent heat flux retrievals degrade compared to the drier Goodwin, Bondville, and Mead sites.

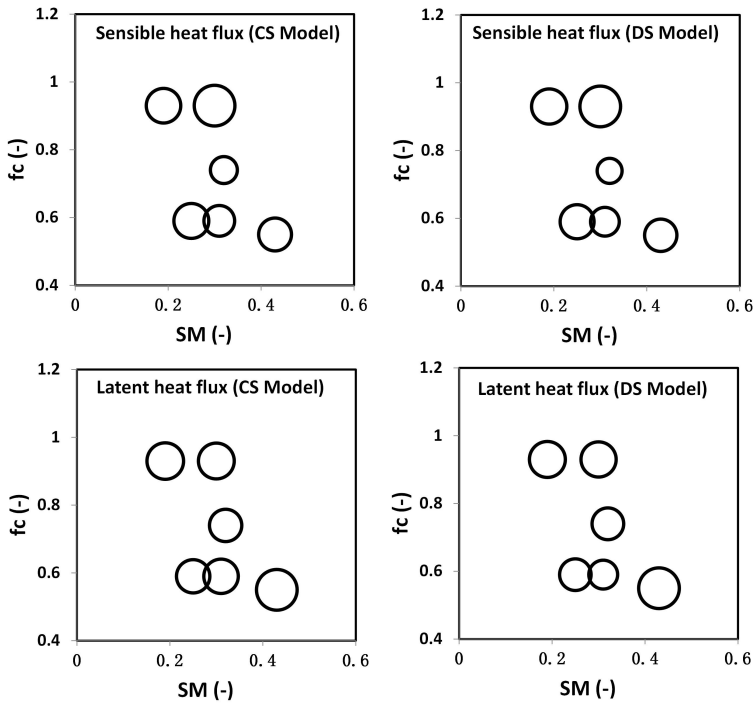

Figure 5. The relationship between the RMSE of turbulent heat flux estimates at each site and its soil moisture (SM) and vegetation cover fraction (f_C). Circle size is determined by the RMSE of flux estimates at each site (larger circles indicate higher RMSE values).

In another study, Crow and Kustas (2005) tested only the CS VDA system with the force-restore equation as an adjoint (VDA-FR) over a range of vegetative and hydrological conditions in the southern U.S. They found that performance of the CS VDA-FR framework degraded over densely vegetated and/or wet sites, and suggested additional land surface information (e.g., leaf area index, LAI) is required to accurately predict surface heat fluxes in densely vegetated and wet sites. In comparison to the Crow and Kustas (2005) study, this project tested both the CS and DS VDA systems with the full heat diffusion equation (instead of the parsimonious force-restore equation) over six sites across the USA. Since even the DS scheme (that uses LAI) cannot perform robustly in densely vegetated/wet sites, it is suggested to assimilate soil moisture or rainfall observations within the VDA scheme in future studies.

Impact of Climate Change on Surface Heat Fluxes

In addition to LST, which lies at the heart of the surface energy balance equation and has information on the partitioning of available energy among the surface energy balance components (Bateni and Entekhabi, 2012a, 2012b), LAI variations (used only in the DS model) control this partitioning (Segal et al., 1988; Alfieri et al., 2009; Bateni et al., 2013b). In this section, a number of sensitivity tests are performed to understand the impact of changes in LST and LAI on the surface turbulent flux estimates. The main goal of sensitivity tests is to provide insights into the effect of variations in LST and LAI (due to climate change) on the heat fluxes.

The Bondville site is selected for this purpose in this study. In the first set of tests, LST observations are varied by ±2, ±4, ±6, ±8, and ±10 K from their nominal values and are used in the CS and DS schemes to estimate turbulent heat fluxes. Figure 6 shows the sensitivity of *H* and *LE* estimates from the CS and DS schemes to uncertainties in LST. For the CS approach, increasing LST by 2, 4, 6, 8, and 10 K leads to a 13.0%, 18.3%, 23.0%, 33%, and 37.8% reductions in *H* and a 10.9%, 22.8%, 32.1%, 39.9%, and 46.9% increase in *LE*. On the other hand, decreases in LST by 2, 4, 6, 8, and 10 K causes *H* to be decreased by 12.4%, 27.5%, 40.1%, 48.8%, and 55.1%, and causes *LE* to be increased by 9.9%, 17.9%, 22.9%, 26.1%, and 28.3%.

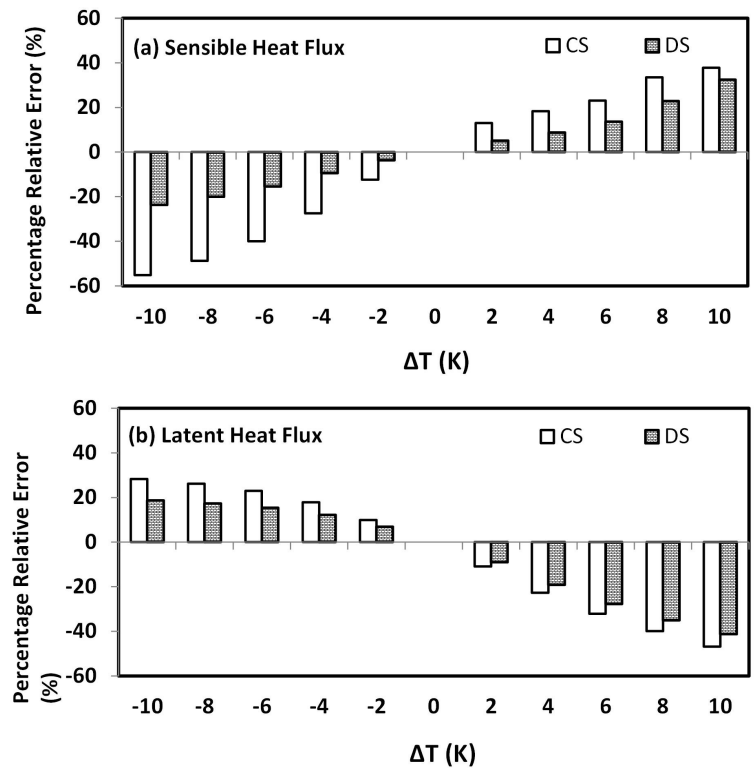

Figure 6. The percentage relative error of estimated sensible heat flux by different sensitivity tests accounting for variations in LST. The original run sensible heat flux estimates are obtained by the CS and DS models with nominal LST observations at the Bondville site.

As indicated in Figure 6, the estimated turbulent heat fluxes from the DS scheme are less sensitive to uncertainties in LST (i.e., the DS model performs better than the CS model when biased LST data are assimilated). For example, *H* and *LE* estimates vary 13.6% and 27.8% as LST becomes 6 K larger than its nominal value.

To assess the effect of variations in LAI on the sensible and latent heat flux estimates, the nominal LAI values are varied by ±20%, ±50%, and ±100% and are used in the DS model. Since the CS model does not use LAI, the sensitivity tests herein are performed with the DS approach only. The sensitivity of estimated sensible and latent heat flux to variations in LAI is indicated in Figure 7. Decreasing LAI by 20%, 50%, and 100% yields a 4.2%, 8.1%, and 13.1% increase in sensible heat flux and a 3.8%, 8.0%, and 18.1% reduction in latent heat flux. Also, the DS model tends to yield larger errors when fed with underestimated leaf area index values. Overall, all of

these results clearly demonstrate that the correct specification of LST and LAI play an important role in the accurate retrieval of turbulent heat fluxes. These findings also allow us to quantitatively characterize the effect of uncertainties in LST and LAI on the turbulent heat flux estimates.

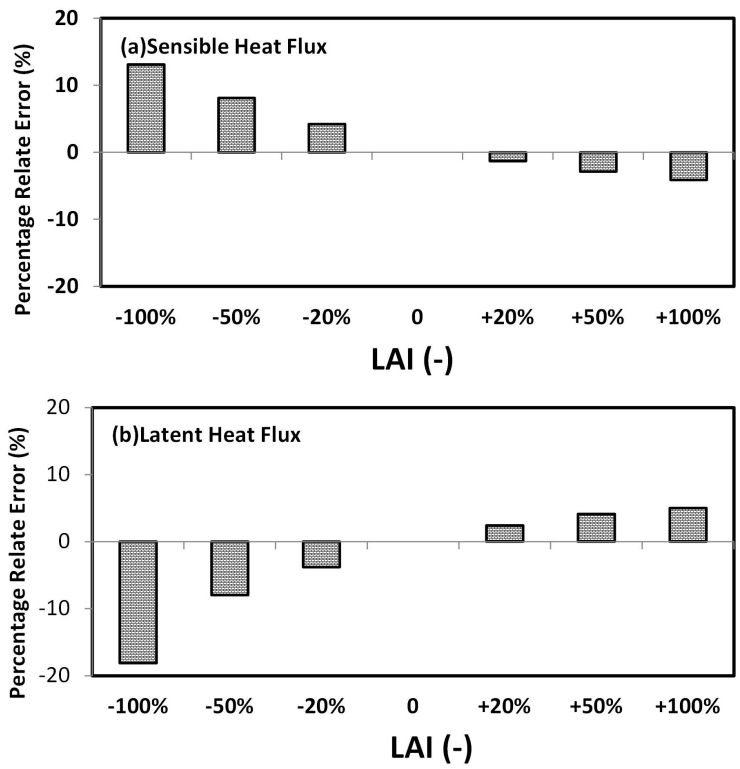

Figure 7. (a) The percentage relative error of estimated sensible heat flux by different sensitivity tests accounting for changes in leaf area index (LAI). The original run sensible heat flux estimates are obtained by the CS and DS models with the nominal LAI observations, (b) The same as in Figure 7a but for latent heat flux.

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Temporal and spatial effects of sewage outfalls on the ecosystem health of coastal waters offshore of Honolulu

Basic Information

Title:	Temporal and spatial effects of sewage outfalls on the ecosystem health of coastal waters offshore of Honolulu
Project Number:	2014HI432B
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End Date:	2/28/2016
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Research Category:	Biological Sciences
Focus Category:	Ecology, Conservation, Management and Planning
Descriptors:	None
Principal Investigators:	Julie Helen Bailey-Brock

Publication

1. There are no publications.

Problem and Research Objectives

The Sand Island Wastewater Treatment Plant and the Honouliuli Wastewater Treatment Plant are primary treatment systems that treat effluents to be discharged a few kilometers offshore of Honolulu. The assessment of biological integrity of Hawaii's coastal waters near to sewage outfalls is a component of water quality regulation and protection. Many types of marine organisms have been used as indicators of biological integrity but the macrobenthic soft-bottom communities have been chosen to provide a reliable measure of coastal water health near the sewage outfalls (e.g., Ambrose et al. 2009, 2011, 2015).

The use of abundance and diversity of macrobenthic species in a multivariate context is an indicator of biological integrity but a measure of ecosystem function has only been accessed when the polychaete species are classified into feeding categories (Fauchald and Jumars 1979). Energy resources gained by these different feeding methods go into reproduction and may guarantee the survival and structure of populations. Despite the value of reproduction in maintaining the equilibrium of populations, it has never been investigated as a biological measure of ecosystem health. For this reason, there is a need to understand the long-term effects of the sewage discharge on the marine ecosystem function by evaluating the reproductive capabilities of selected marine worms.

The intent of this proposal is to investigate the spatial (near the outfalls diffusers or far field at reference stations) and temporal (along 11 years of data collection) effects of the outfalls on the reproductive capabilities of syllid polychaetes by using the data recorded in the University of Hawaii's Water Resources Research Center's Project Reports. This research aims to test the hypothesis that there will be spatial and temporal differences in the reproductive capabilities of syllid polychaetes in both outfall locations.

Methodology

The reproductive data of polychaetes present in the reports of the Sand Island and Barbers Point ocean biomonitoring projects for the period of 11 years were used. Samples from Barbers Point outfall have been collected during the winter and the spring months and samples from Sand Island outfall have been collected during the summer and the fall months. Syllids were selected because of its abundance and frequency of mature species. The species *Pionosyllis heterocirrata* and *Sphaerosyllis* sp. G were the most abundant and frequent species in both outfall locations. The sampling stations were categorized based on the proximity of the outfall diffusers. For instance, the Sand Island outfall sampling stations C2, C3, D2, D3, E2, and E3, and the Barbers Point outfall sampling stations HB2, HB3, and HB4 were *a priori* classified as 'near' the diffusers while all the other stations were classified as 'far' from the diffusers. Eleven years of data for the two species were retrieved and tabulated for the number of immature individuals and the number of individuals presenting gametes, eggs or attached embryos.

An analysis of similarity (ANOSIM) was performed to test the statistical significance of the *a priori* defined groups (i.e., 'near' and 'far' stations to verify for spatial variability and 'year' to account for temporal variability). ANOSIM was performed using the Bray-Curtis similarity coefficient with non-standardized and untransformed data in the PRIMER 6.0 software.

Principal Findings and Significance

In the Barbers Point outfall, the species *Pionosyllis heterocirrata* had an average of 18% (ranging from 1.5–49.2%) of the population comprised of mature individuals throughout the 11-year period while *Sphaerosyllis* sp. G had an average of 16.6% (ranging from 0–43%) of mature individuals in the population. In the Sand Island outfall, the species *Pionosyllis heterocirrata* had an average of 10% (ranging from 1–45%) of the population comprised of mature individuals throughout the 11-year period while *Sphaerosyllis* sp. G had an average of 34% (ranging from 10–64%) of mature individuals in the population. Gherardi et al. (2005) report a maximum percentage of mature specimens of the syllid *Exogone naidina* for 37% of the population in the Mediterranean.

Figure 1 shows a variation of a number of individuals showing maturity throughout the years for both species. Both species show reproductive capabilities year round with peaks during the months of March/April and August/September when most samples were collected. Davis (1987), studying polychaete communities at the Sand Island sewage outfall, found that *Pionosyllis heterocirrata* had large proportions of adult individuals in May, suggesting that this species reproduces during the spring. Two peaks of reproduction in a year are common for many tropical marine invertebrates but a year long study needs to be done to verify for non-reproductive periods.

Results of ANOSIM show that there were no significant differences between the reproductive capabilities of both species from 'near' and 'far' field stations from the outfalls and throughout the 11-year period (Table 1). Although the Global R values were low and the *p* values were not statistically significant, there were more accentuated temporal than spatial differences.

Table 1. ANOSIM results showing Global R and *p* values.

Outfall	Species	Spatial (proximity to diffuser)		Temporal (2002/2003–2013)	
		Global R	*p* value	Global R	*p* value
Barbers Point	*P. heterocirrata*	-0.156	0.1	0.076	0.08
	Sphaerosyllis sp. G	-0.059	0.845	-0.034	0.819
Sand Island	*P. heterocirrata*	-0.011	0.62	0.025	0.09
	Sphaerosyllis sp. G	-0.027	0.828	0.015	0.8

This progress report shows that the two analyzed species reproduce year round and can be good indicators for ecological disturbances. There were no significant differences in the reproductive capabilities of these two species in samples collected 'near' and 'far' field from the outfall diffusers and throughout the 11-year period. Temporal differences seem to be more accentuated than spatial differences. The next step would be to increase the number of species (possibly grouping into genera would give better results and the data would not be so patchy) and to perform additional analysis using the environmental variables available in the reports (e.g., chemical characterization of the sediments and grain size) and to verify if the reproductive success is correlated to any of them.

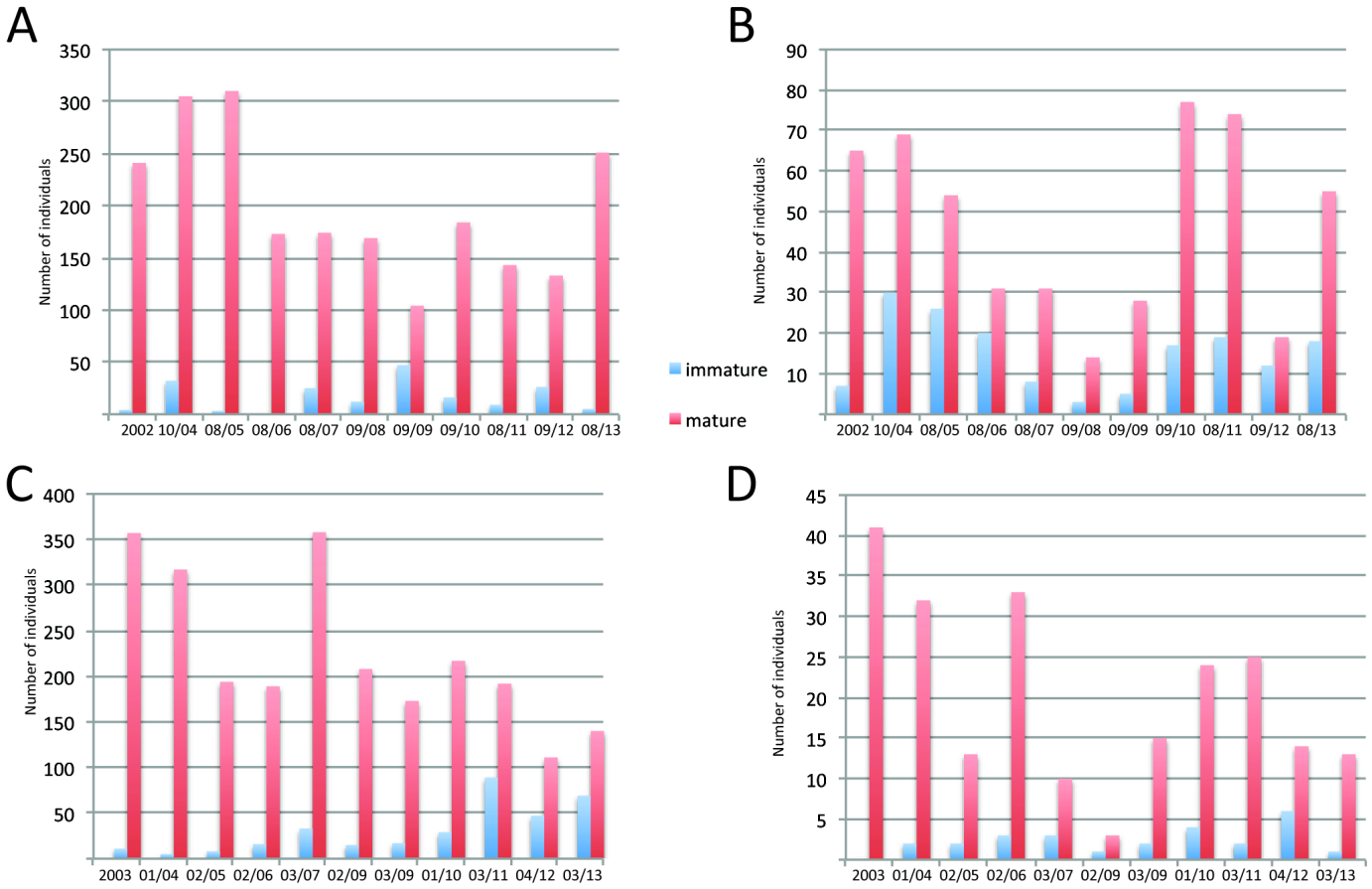

Figure 1. Number of mature and immature individuals during the study years for Sand Island outfall: A) *Pionosyllis heterocirrata*, B) *Sphaerosyllis* sp. G., and for Barbers Point outfall: C) *Pionosyllis heterocirrata*, and D) *Sphaerosyllis* sp. G.

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Managing for multiple ecosystem services with changing land use in West Maui

Basic Information

Title:	Managing for multiple ecosystem services with changing land use in West Maui
Project Number:	2014HI433B
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Focus Category:	Water Quality, Water Use, Sediments
Descriptors:	None
Principal Investigators:	Kirsten Oleson

Publications

1. Stock, J., K. Falinski, and T. Callender, T., 2015, Reconnaissance sediment budget for selected watersheds of West Maui, Hawaii, USA. Open File Report, USGS.
2. Peng, M,. and K. Oleson, Economic loss from coastal water quality problems in Hawaii. (in preparation)

FINAL REPORT

Managing for Multiple Ecosystem Services with Changing Land Use in West Maui

May 2015

Kirsten Oleson

WRRC-2015-05

Project Number: 2014HI433B

Water Resources Research Center
University of Hawaii at Manoa
Honolulu, Hawaii

Introduction

Coastal water quality is an integral part of the Hawaiian landscape and economy, affecting both coral ecosystem health and visitor satisfaction. Hawaii's coastal water supports an abundance of marine life while drawing visitors from around the world. However, it is threatened by changing land use practices and increased land-based pollutants such as nutrients and other contaminants. In particular, the land use of West Maui Watershed is in transition from agricultural to suburban. Many hectares of former sugarcane and pineapple land are currently fallow, and previous management practices for irrigation and erosion control have been abandoned. An additional 7,000 homes scheduled to be built in the watershed within the next 15 years will further burden scarce freshwater supplies and impact the environment.

Managers in West Maui recognize the need to balance development and conservation goals. Past and future development tax scarce water resources and threaten the freshwater quality, affecting important ecological functions that in turn benefit local communities. To preserve biodiversity and water-related ecosystem services such as groundwater recharge, the West Maui Mountain Watershed Alliance preserves and manages the upper forests. To mitigate the loss of fisheries, recreation, coastal protection, and biodiversity (i.e., ecosystem goods and services from coastal systems), NOAA prioritized the coral ecosystem at the base of the Wahikuli and Honokowai Watersheds and is funding an initiative that actively seeks ridge-to-reef solutions to control land-based sources of pollution affecting the reef. The objective is to study the significant hydrological links between the reef and land-based activities—namely groundwater recharge, surface water flow, sediment loads, and nutrient loads.

Despite ongoing management actions, there is a critical need to evaluate the potential trade-offs posed by alternative resource management strategies across a broad suite of ecosystem threats, resource uses, and stakeholder groups. Because of their critical importance in this watershed, and because they are the links between land management and reef health, our initial focus is estimating land-based source pollutants (i.e., sediments and nutrients) and including these results in a decision support tool. This decision-support tool needs to be designed to reveal biophysical impacts (i.e., erosion, runoff, and infiltration) that result from specific land management actions (e.g., land use, adoption of best management practices, and restoration).

In addition, the economic data that links the hydrologic models to the economic value of the service is unavailable for many of the hydrologic ecosystem services in Hawaii, including water quality. Nearly eight million visitors stayed in Hawaii in 2012, for a combined 74 million visitor-days (HTA 2012). Out-of-state Americans spend on average $167 a day, and Japanese on average $310 a day (State of Hawaii 2011). Across the state, an astounding 302 closures occurred in 2009 (EPA 2010). If visitors decided not to visit Hawaii as a result of frequent coastal water contamination events, the economic impact would be negative for the state economy where tourism comprised 29% ($15 billion) of the economic output in 2012 (State of Hawaii 2011). A 2011 study found that more than 80% of American visitors participate in beach-related recreational activities, more than 25% surf, over 50% snorkel and dive, and 5% jet-ski and/or windsurf (HTA 2011), yet did not indicate the effect of water quality on participation in these activities.

Problem and Research Objectives

In order to predict the effect of land use change on water quality, and to estimate the impact that water quality has on the tourism economy, we conducted two field studies to support efforts to quantify and map water quality-related ecosystem services in West Maui.

Common hydrological models used to predict sediment export and water quality at the coast are difficult to adapt because of Hawaii's small watersheds and resulting flashy streams. This potentially adds large uncertainty to the ecosystem service tools in consideration. It remains unclear which erosion process (sheet erosion, channel erosion or gully erosion) contributes the most to the overall sediment budget. Previous work (Hill 1996, Stock et al. 2010) estimated contributions from different sediment processes in Hanalei, Kauai and Kawela, Molokai using comprehensive field studies and modeling efforts. West Maui, however, is data poor, and lacks rain gauges, flow measurements, and total suspended solids data to calibrate and validate daily, event-driven models like the Soil and Water Assessment Tool (SWAT) and the Gridded Surface Subsurface Hydrologic Analysis (GSSHA). There have been no field studies that assess the geomorphological characteristics of the five priority watersheds. The objective of this research was to conduct initial rapid geomorphological surveys, and to estimate contributions from channel erosion. A simple model based on the Universal Soil Loss Equation (USLE) and Borselli's sediment delivery ratio model (InVEST) was chosen to model sediment export. The field surveys will be used to spatially calibrate the output of the model.

Estimates that capture the lost economic value of water quality problems can inform management and help draw attention to the broader implications of land-based source pollution. Various valuation methods could be used to explore the economic losses (or gains) from the environmental attributes of the nearshore system. In environmental economics, non-market valuation is used to estimate values for environmental goods and services that are not readily apparent in the market. Stated or revealed preference models are commonly applied to elicit willingness to pay. This project identifies candidate valuation approaches and demonstrates the methodology in a pilot study on Oahu.

Methodology

Improving Sediment and Nutrient Models with Field Validation

During the summer of 2014, we traveled to West Maui with U.S. Geological Survey (USGS) geomorphologist Johnathan Stock and Sustainable Resources Group International, Inc. (SRGII) hydrologist Andrew Hood. The purpose of the field visit was to identify sources of sediment and to better understand the hydrologic connectivity between sediment sources and the intermittent stream system. About four miles of the two stream systems (Wahikuli and Honokowai Streams) were surveyed, in addition to neighboring fields, urban drainage systems, reservoirs, and outfalls. We identified features on the landscape to correspond to the remote imagery and sediment export modeling efforts.

In August 2014, four sites in the Wahikuli Stream were chosen to install erosion pins to measure the erosion rates of the stream channel walls. At each site, ten 8-cm pins were gently hammered into the sidewall. The sites were chosen to represent reaches of the stream where the bank was exposed. The sites were evaluated for changes in early April 2015 using calipers. An

additional field survey will be conducted to estimate what percentage of the reaches are exposed bank.

Figure 1. Installation of erosion pins at Site 3 on Wahikuli Stream, Maui.

Sediment Export Modeling Efforts

We collaborated with Natural Capital Project programmers and scientists to beta test new sediment delivery algorithms for the InVEST sediment delivery model. In the summer of 2014 we set out to determine the appropriate models for other types of erosion processes not included in InVEST's sediment retention module, and to compare what method might be most appropriate for Hawaii to model sediment transport processes. We collected data from collaborators and public datasets (USGS, Natural Resources Conservation Service [NRCS]) to evaluate previous studies in Hawaii that can estimate the importance of those processes. We conducted an extensive literature review of sediment retention, Soil Conservation Service (SCS) Curve Numbers, C-factor, and K-factor variables in Hawaii and other tropical mountainous locations, and incorporated those new parameterizations in the sediment delivery model.

In order to run the InVEST model, significant effort was made to improve input data to capture important processes that affect sediment and nutrients. The input data for the InVEST model included soil data from the Soil Survey Geographic Database (SSURGO), and the Costal Change Analysis Program (C-CAP) high resolution (2.4 m) 2005 land use data. We improved the input data for the InVEST model, rainfall factor information from the U.S. Department of Agriculture (USDA), and a digital elevation model (10 m) from the USGS. We compared sub-watershed designations to estimate an appropriate stream accumulation area. We added new land use classes to separate sugarcane, pineapple, grazing, and fallow agriculture based on the expert opinion of W. Nohara (Maui Land and Pineapple; personal communication, 2014). We also modified the land use designation in C-CAP for golf courses derived from LandFire.

We compared the static InVEST model to daily time-step models that are also based on the USLE input data, including SWAT, Nonpoint-Source Pollution and Erosion Comparison Tool (N-SPECT), and GSSHA. The input data was the same for each model, and calibrated first using Kawela, Molokai data available from the USGS. The model was run for the Honokowai Watershed. We collected rainfall data from a diverse array of partners, including community members, private landowners, and USGS monitoring sites.

Valuation Study

First, we evaluated alternative possible valuation methods via a thorough literature review. We considered choice modeling, contingent valuation, and travel cost method—all stated choice methods that are commonly used to value (coastal) water quality and recreation elsewhere (Arrow et al. 1993, Moncur 1975, Ofiara and Brown 1999, Krosnick et al. 1996). Choice modeling was determined to be the most suitable method. It allows several environmental attributes to be valued at the same time using believable scenarios realistic to the participants (Bishop et al. 2011, Loomis and Santiago 2013). This study closely follows Loomis and Santiago (2013), who conducted both choice modeling and contingent valuation to estimate the non-market value of beaches in Puerto Rico.

Next, having chosen the appropriate method, we identified the beneficiary group (coastal recreationalists) whose consumer surplus or loss (economic jargon for benefit or cost) we wanted to estimate. We designed a choice experiment. The experiment reflects environmental attributes of concern to recreationalists and associated levels, which we set via literature and discussions with experts. Specifically, the attributes considered were (1) water quality, (2) water clarity, (3) coral reef cover, and (4) fish diversity set at levels: high, medium, and low (quantitative metrics for these qualitative levels were specified, based on ecological and water quality experts' advice). We also included numerous additional questions to capture respondent demographics, beach/coastal uses, as well as attitudes and perceptions. We received approval from the International Review Board (IRB). In fielding the survey, we used lifeguard statistics (EPA 2007, 2010, 2011, 2012a, 2012b, 2013a, 2013b; HTA 2011, 2012) to estimate beach attendance and divided surveys proportionately across Oahu beaches. A total of 263 successful in-person interviews were conducted between June and November 2014. The majority of the interviews were conducted in Waikiki (47% of the total), followed by the remaining south shore beaches (23%), Oahu's north shore (13%), Waianae coast (11%), and Windward Oahu (6%). The refusal rate was 11%.

The results were analyzed by logistical regression using the statistical package STATA.

Principal Findings and Significance

Field Observations and Interpretations in West Maui

The former sugarcane fields in West Maui did not show evidence of being connected to the stream. A well-developed grass and haole koa stream buffer would likely prevent any connectivity during a rain event. Shallow landslides in Honolua watersheds may have been contributors to overall sediment export to Honolua Bay. Gullying along the makai ridges, past former agricultural land, may have been initiated due to excessive trail erosion or when the road was created many years ago. Field 52 did not show evidence of connectivity to Honolua stream, but legacy deposits from push piles may still exist on the hillslope.

Bank erosion was visible and common throughout the stream bed. Roughly, more than 25% of the banks had areas that exposed silt to stream water. Marks on the trees, leaf litter deposition, and the red coatings on the rocks shows where the water level has reached in the last decades. The water level seems to rise approximately 2 to 3 feet (at its highest). Grass root exposure and emergent seedlings visible in April indicate that the events might take place on a sub-year time scale in the Wahikuli Stream.

Pig activity was clearly evident in many of the upper watersheds in forested areas (i.e., Napili, Honokowai, and Wahikuli Gulch). Pigs specifically were observed rutting in dry stream beds, which often were under large fruit-bearing trees, suggesting that pigs are able to remove the natural armoring of the stream and expose the sediments below. Feral pigs are likely to dig rather deep as they eat roots and fruits from the wild lilikoi, mango, coffee, and avocado trees. The red marks on the rocks, especially surrounding the pools, may indicate that pigs are responsible for significant disturbance that accelerates how fast the stream is cutting into the soil layer.

There were very few, if at all, places where the bedrock was visible in this stream. We observed that the trails and roads directly connect to the stream. Usually the connection to the stream was limited to intersecting trails; however, in some watersheds to the north on the former pineapple land, the roads were so close to the stream that the kickouts drain directly into the stream. The roads that were adjacent to the streams have water bars that may contribute to the sediment loads. In contrast, the roads that were disconnected and/or run parallel further away from the streams are relatively distant sources.

We viewed examples of two different types of streams that accessed fine sediments. At one end of the spectrum, the main branch of the Honokowai Stream and Wahikuli Stream showed evidence of bank erosion into silty deposits, but was dominated by larger boulders and cobbles that likely originated from rockfall in the upstream reaches. Exposed bedrock was common and evidence of a stage height of more than a meter was seen. The second type of stream was observed in the lower reaches of the southern branch of the Honokowai and Mahinahina Streams. The low gradient stream cut through the fine sediment deposited throughout the valley floor. Multiple pathways for stream flow were seen. These deposits were located just before the reservoirs.

The above facts suggest that the West Maui Watershed is not source limited for sediments, but instead transport limited. In this case, sediment transport is the limiting factor for sediment export.

Using a field infiltrometer, we were able to assess the hydraulic conductivity data found in the SSURGO database. Six points were measured in the Wahikuli watershed on former corn fields. Estimates of the hydraulic conductivity on these fallow agriculture fields were approximately 10 to 30 mm/hr, similar to the value of the 30 found for these fields in SSURGO. An analysis of rainfall events recorded in the seaward, lower parts of the Wahikuli watershed, indicate that storm events that mobilize surface runoff for these fields are few (one per decade), which indicates the fields are not consistent new sources of deposits into the channels.

Initial bank erosion estimates between August and April 2015 showed an average of 5 mm lateral wall erosion during this period. Subsequent readings will help determine an annual rate of erosion of the bank walls, and future studies will be able to more accurately assess the percentage of the reaches that are exposed.

The implications for modelling are (1) channel erosion models that are developed using flow estimates are needed for accurate assessments of total sediment load to the coast, and (2)

parameterizing the forest as having a higher export than traditionally estimated for non-disturbed forests in non-tropical conditions is appropriate given the presence of pigs and trails. Pig activity, in particular, can severely change the erodibility of a soil profile. This follows the work of Cheng (2007) in Hanalei.

Sediment Export Modeling

Figure 2 shows the output of the model calibrated with the new parameterizations, including increased sediment export due to forest and grassland disturbance. Sediment export at the coast ranged from 27 to 4,470 tons. Notably, the Kaopala watershed export was significantly higher than the surrounding subwatersheds. This result was identified by field observations in the USGS Open-File Report (Stock 2015).

Initial results suggest that InVEST and N-SPECT have comparable results, but that GSSHA, which estimates sediment delivery per rain event, predict values that are several orders of magnitude greater than the previous two models.

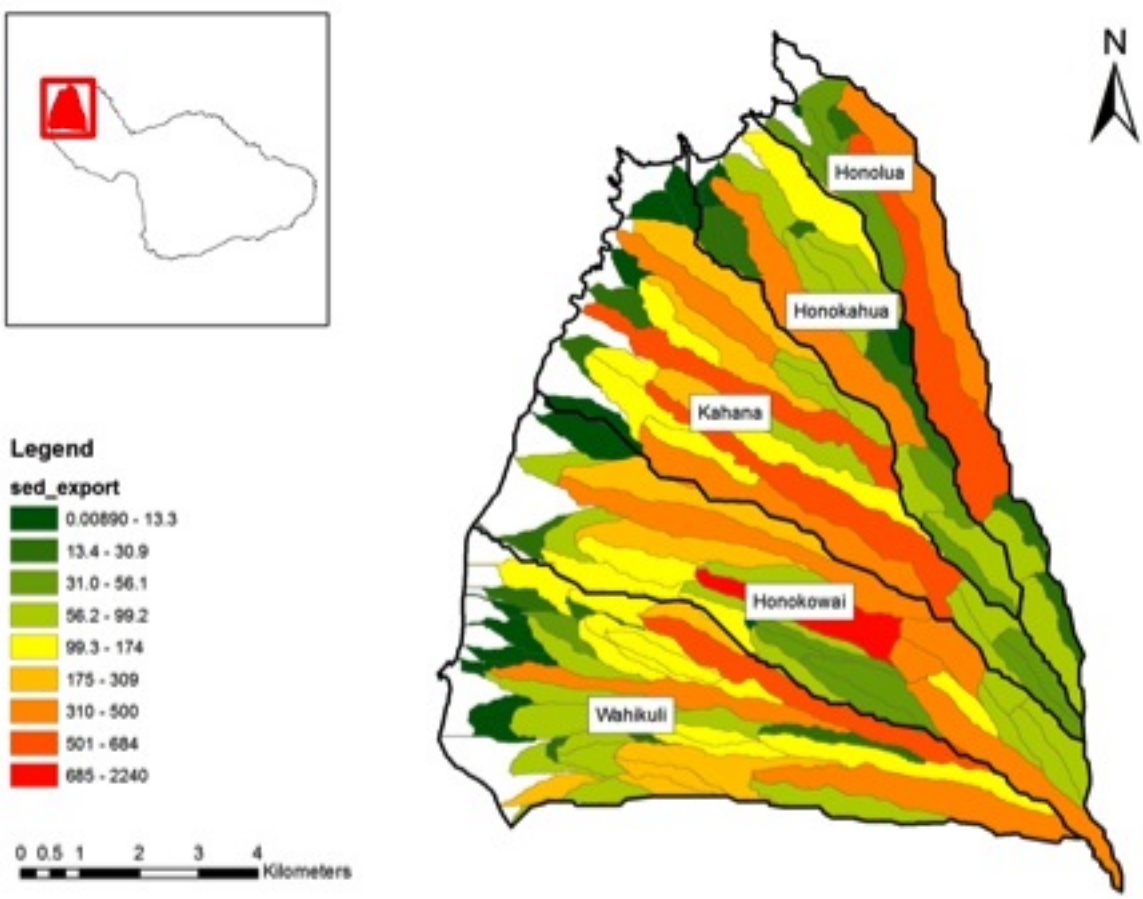

Figure 2. InVEST Sediment Delivery Model results in tons per year for West Maui.

Valuation Field Study

The results of the multi-nominal logit (MNL) regression revealed recreationalist are willing to pay for improved environmental conditions across all attributes in the study (Figure 3). We found that water clarity was the most important factor, followed by water quality. In particular, respondents were especially interested in the "high" levels of water clarity and quality. The diverse responses demonstrated a significant preference for water clarity and high levels of coral reef cover. In a latent class analysis, the respondent population was largely uniform, with greater than 75% belonging to the same class.

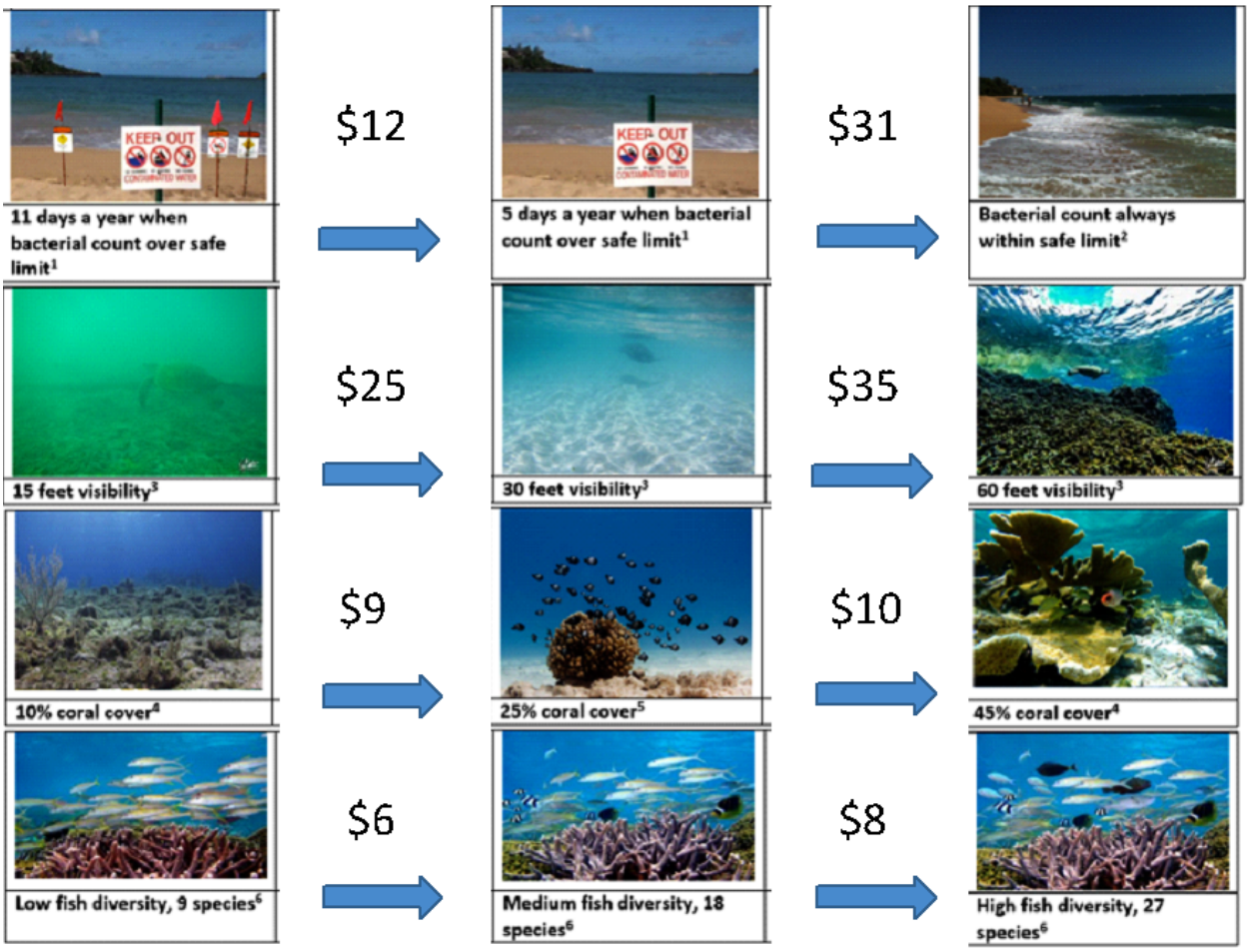

Figure 3. Willingness to pay for varying qualities of environmental conditions of the Oahu coastline (on a per person per trip basis).

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Tracing Interconnectivity Between High-level and Basal Groundwaters in West Hawaii

Basic Information

Title:	Tracing Interconnectivity Between High-level and Basal Groundwaters in West Hawaii
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Start Date:	3/1/2014
End Date:	2/28/2016
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Focus Category:	Groundwater, Hydrogeochemistry, Hydrology
Descriptors:	None
Principal Investigators:	Craig R Glenn

Publication

1. There are no publications.

Problem and Research Objectives

Recent rapid development in the North Kona District of West Hawaii has raised concerns regarding the sustainability of the region's groundwater resources in the face of increasing demand. A large portion of the region's municipal water supply is withdrawn from wells tapping a high-level groundwater system (Oki 1999). However, the effects of withdrawals from this high-level aquifer on the underlying and adjacent basal groundwater system, which itself sustains the region's unique coastal ecosystems while also being utilized for municipal, industrial, and irrigation purposes, are not well understood. Several previous scientific studies of groundwater in the North Kona district (Oki 1999, Bauer 2003, Kelly 2012) have proposed that the high-level groundwater system in this area recharges the basal lens and that withdrawals from the high-level system could potentially impact the basal system. However, recent reports done in support of environmental impact statements for development in the region (e.g., Nance, 2013) have challenged these findings by citing evidence for an impermeable barrier separating the basal and high level systems. Additional research into the relationship between basal and high-level groundwater is needed to better assess the merit of these competing claims.

Concerns over the potential for future development and associated increases in groundwater withdrawals to impact the groundwater-dependent coastal ecosystem of Kaloko-Honokohau National Historical Park resulted in the National Park Service submitting a petition in September 2013 for the Hawaii Commission on Water Resource Management (CWRM) designate the Keauhou Aquifer as a "Ground Water Management Area." This designation would place more stringent controls on groundwater development and withdrawals in the region and has provoked controversy between proponents of development and conservationists. This proposed project should yield solid insight into the relationship between basal and high-level groundwater in this region and assist the CWRM in determining the future regulatory status of the Keauhou Aquifer as well as strategies for its sustainable use.

The fundamental nature of this project is to continue the investigation into the use of water isotopes as conservative tracers of groundwater flow and mixing that began under NSF award #0903833 (IMUA III: Pacific High Island Evolutionary Biogeography: Impacts of Invasive Species, Anthropogenic Activity and Climate Change on Hawaiian Focal Species). Work under that grant included determination of δ^2H and $\delta^{18}O$ values for 129 groundwater and coastal ocean samples (to be used in mixing analysis) as well as the establishment and sampling at 6-month intervals of 8 cumulative precipitation collectors across the region Continued sampling of these collectors in the present work resulted in improved insight into temporal variation in δ^2H and $\delta^{18}O$ values in precipitation in this region, and has provided a robust data set (> 2 years for all collectors) for use in mixing analyses.

Methodology

The cumulative precipitation collectors used in this study were designed to prevent evaporation of accumulated rainfall over a long-term deployment. The design is based on collectors used for the same purpose by Scholl et al. (1996) and consists of a 5 gallon HDPE tank with a 76 or 110 mm diameter funnel affixed to the lid mounted on a wooden base with metal legs. Prior to deployment, a 1 cm layer of mineral oil was added to each collector to

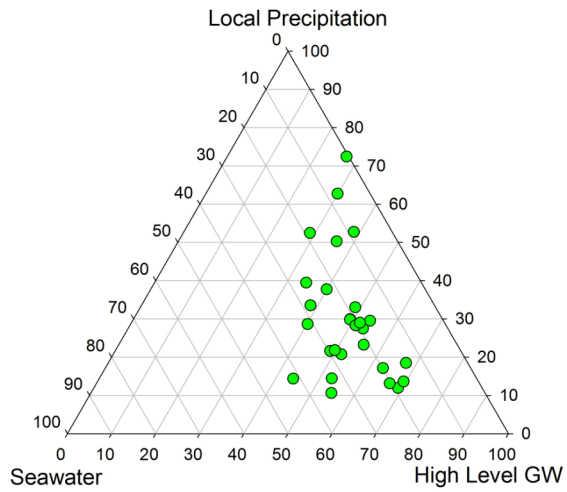

Figure 1. End-member mixing analysis using water isotope values indicates that basal groundwater sample in the Keauhou aquifer consist of a large portion of high-level groundwater.

prevent evaporation of collected precipitation and the apparatus is wrapped in a trash bag to prevent sun exposure. The mount was secured to the ground by weighting the legs with rocks, and, if ground conditions permitted, digging shallow holes into which the legs are placed. Locations near currently active precipitation monitoring stations were utilized whenever possible in order to evaluate the efficiency of the cumulative precipitation collectors with respect to the existing rain gauge.

Once deployed, the collectors were sampled at 6-month intervals. During sampling, collected precipitation was withdrawn from a spigot located near the bottom of the bucket and measured in a graduated cylinder. The protective trash bag and mineral oil layer was replaced upon completion of sampling. We analyzed the samples for δ^2H and $\delta^{18}O$ at the University of Hawaii Stable Isotope Biogeochemistry Lab using our Picarro cavity ring-down mass spectrometer. Our analytical precision for this method is evaluated by comparison of duplicate samples and was typically <0.1‰ for $\delta^{18}O$ and <0.6‰ for δ^2H.

The determination of δ^2H and $\delta^{18}O$ values for the area's precipitation, groundwater, and seawater provides the means to assess the contribution of high-level groundwater to the basal system via end-member mixing analysis. For the purpose of this analysis, seawater, local precipitation (approximated by the volume weighted average of precipitation collected across the basal aquifer's elevation gradient), and high-level groundwater were employed as the end-members. The percent contributions of these three end-members to each basal groundwater sample were determined analytically using our δ^2H and $\delta^{18}O$ values as tracers (e.g., Christophersen and Hooper 1992, Hooper 2003, Liu et al. 2004).

Principal Findings and Significance

Mixing analysis of basal groundwater in the Keauhou aquifer using water isotopes was completed and presented as a poster at the Ocean Sciences Meeting in February 2014, just prior to the commencement of the reporting period. The principal finding of this analysis was that basal groundwater in the Keauhou aquifer contains a significant portion of recharge from the high-level aquifer (Figure 1). This finding attracted a great deal of interest from

stakeholders in the debate regarding the designation of the Keauhou aquifer and was later validated by the published results of Tillman et al. (2014), which used our methodologies to come to the same conclusions.

Final precipitation collector sampling took place in December 2014. These samples have been analyzed and integrated into previously acquired data yielding the most robust and comprehensive meteoric water line (Figure 2) and water isotope/altitude relationship (Figure 3) to date. Our newly acquired data was used in updated basal groundwater mixing scenarios that were provided to Paul Eyre of CWRM to assess the validity of various conceptual models of groundwater flow in the Keauhou aquifer. Additionally, the data acquired by this study has been utilized in presentations by Delwyn Oki (USGS) and Donald Thomas (UH) during CWRM contested case hearings regarding the designation of the Keauhou aquifer as a special management area in late 2014. Our data is also currently being shared with and utilized by Robert Whittier of the Hawaii Department of Health to develop a new model of groundwater flow in West Hawaii for the purpose of evaluating source water protection.

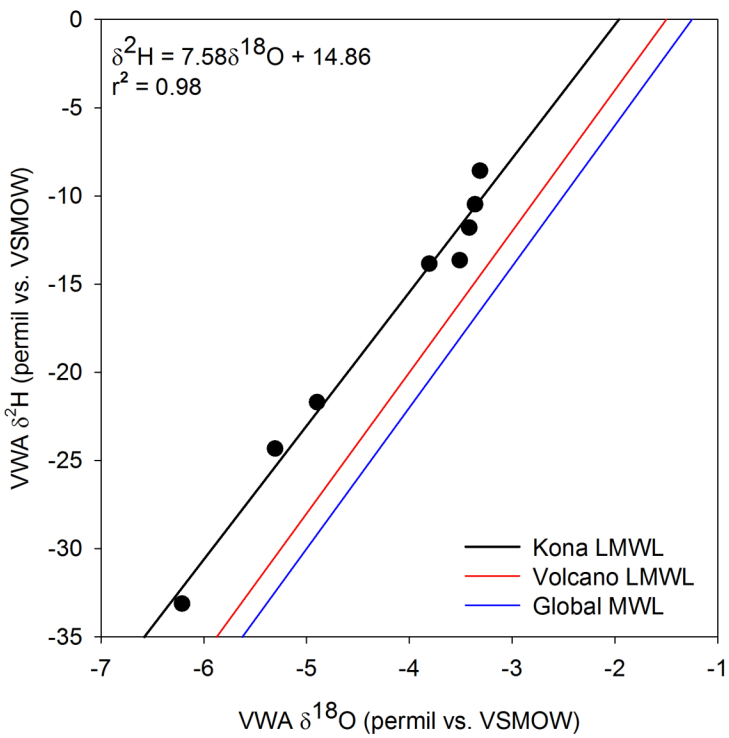

Figure 2. Local Meteoric Water Line (LMWL) determined for West Hawaii based on >2 years of data.

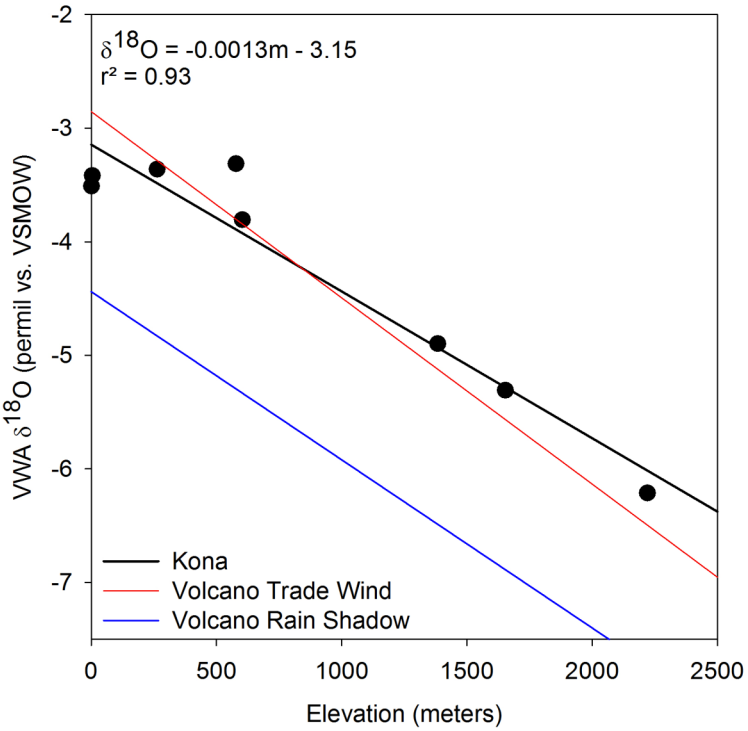

Figure 3. Relationship of $\delta^{18}O$ values in precipitation with elevation determined for West Hawaii based on >2 years of data.

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Tillman, F.D., D.S. Oki, A.G. Johnson, L.B. Barber, and K.R. Beisner, 2014, "Investigation of geochemical indicators to evaluate the connection between inland and coastal groundwater systems near Kaloko-Honokohau National Historical Park, Hawaii," Applied Geochemistry, 51, 278–292, doi:10.1016/j.apgeochem.2014.10.003.

Assessment of Groundwater Availablity in the Volcanic-Rock Aquifers of Oahu, Hawaii

Basic Information

Title:	Assessment of Groundwater Availablity in the Volcanic-Rock Aquifers of Oahu, Hawaii
Project Number:	2014HI439S
USGS Grant Number:	G14AP00117
Sponsoring Agency:	USGS
Start Date:	9/1/2014
End Date:	12/31/2015
Funding Source:	104S
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Hydrology, Models
Descriptors:	None
Principal Investigators:	Aly I El-Kadi

Publications

1. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2014, “Up and Down: How can we assess hydraulic properties from tidal fluctuations in coastal aquifers?”, Abstract H53B-0845, presented at 2014 Fall Meeting, AGU, San Francisco, CA, Dec 15–19.
2. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2014, “Development of a hydrogeologic framework from tidal analysis of coastal groundwater levels, Hawaii,” 40th American Water Works Association Conference, Honolulu, May 6–9
3. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2013, “Development of a hydrogeologic framework using tidally influenced groundwater levels, Hawaii,” Abstract H11H–1248, presented at 2013 Fall Meeting, AGU, San Francisco, CA, Dec. 9–13.

Problem and Research Objectives

The volcanic-rock aquifers of Oahu supply freshwater to 70 percent of Hawaii's population and most of other needs, including commerce, industry, and U.S. military. The resident population on the island has been increasing while freshwater resources are limited. Because the aquifers are small and are surrounded by saltwater, they have a restricted capacity to store groundwater and are thus particularly susceptible to impacts from human activity, through land-use changes or excessive withdrawals, and climate change (Izuka 2013). Availability of fresh groundwater is limited by the desire to avoid adverse effects on water resources, such as lowering water tables, saltwater intrusion, and depletion of streamflow and submarine groundwater discharge. Quantifying these effects is therefore critical for a successful groundwater management.

The last regional assessment of the water resources in the volcanic-rock aquifers of Oahu was completed during the 1990s (Hunt 1996, Nichols et al. 1996). Since then however, new technologies (computer power, modeling software) and new analysis techniques have been developed, recharge and hydrogeologic information have been updated, and the need to consider effects of climate change has increased. This warrants a revised assessment of the current groundwater availability, of the likely impacts of natural and anthropogenic factors on such availability, and of the effects of these factors on water resources in the future.

The study will utilize a numerical modeling approach of newly available recharge and hydrogeologic information to (1) improve understanding of the most developed regional groundwater-flow system in the main islands of Hawaii, (2) update knowledge of the availability and sustainability of Oahu's groundwater resources, and (3) provide insight into the impacts of human activity and climate change on groundwater resources.

Methodology

For the assessment of Oahu's groundwater resources stored in volcanic rock, an island-wide numerical model that simulates groundwater flow and sharp interfaces between fresh- and saltwater was developed. Although sharp interface codes cannot completely simulate mixing and dispersion in the transition zone, the Saltwater-Intrusion package (SWI2) of MODFLOW 2005 (Bakker et al. 2013) allows simulating multiple sharp interfaces and density layers, and therefore offers a good representation of the transition zone between freshwater and saltwater.

Recent studies of the U.S. Geological Survey have generated new recharge estimates for Oahu for conditions prior to the onset of groundwater development and recent conditions from 2001 to 2010 (Engott et al. 2015). The study also predicted recharge estimates based on future climate conditions, climate models, and IPCC scenarios. Geologic and hydrogeologic data have also been updated through a number of USGS studies (e.g., Oki 2005). Although Hawaii aquifers are vastly heterogeneous, Oahu's hydrogeologic framework can be simplified to three hydrogeologic units: (1) dike-intruded volcanic rock, (2) dike-free volcanic rock, and (3) sediments together with rejuvenated Volcanics. The simplified hydrogeologic units are zones of similar hydraulic properties and hydrogeologic conditions. The altitude of the contact between volcanic rock and overlying sediments has been digitized for the entire island to 6,000 ft below sea level. The structural contours between basalt and sediments facilitate the model grid generation of the hydrogeologic units. Aquifer-property estimates are available from published

model results (Oki 1998, Oki et al. 1998, Oki 2005, Rotzoll and El-Kadi 2007, Whittier et al. 2010), a comprehensive summary of parameter values (Hunt 1996), and a recent analysis of groundwater levels from wells with tidal influence (Rotzoll et al. 2013).

The study also examined the relationship between high-level dike-impounded aquifers and down-gradient Pearl Harbor freshwater-lens aquifers. The numerical model simulated three scenarios: (1) pre-development conditions, (2) average current conditions from 2001 to 2010, and (3) conditions under a future recharge scenario. Model calibration utilized available water levels and salinity profiles, if possible through an automated parameter-estimation routine. Model sensitivity will be implemented to address the influence of uncertainties in the model parameters on results. Part of the work focused on developing Python scripts to create model input files and to analyze results of the model output (Bakker 2014).

The calibrated numerical model will be used to evaluate historical anthropogenic effects (changes in land use and withdrawals) and future effects of climate change (changes in recharge and sea level). The historical anthropogenic effects are the difference between the simulated pre-development conditions and current conditions. The effects will be quantified by changes in water levels and in the freshwater/saltwater interface position, and differences in groundwater fluxes across hydrologic boundaries. Comparison of the results of these scenarios will be the basis for assessing the human impact on groundwater resources of Oahu's volcanic-rock aquifers. Climate change affects groundwater resources in Hawaii by causing changes in recharge and sea level. Changes in recharge alter the groundwater budget, causing changes in groundwater storage and availability. Sea-level rise causes a rise of the freshwater/saltwater interface by displacing the freshwater lens upward and coastal inundation (Rotzoll and Fletcher 2013). The numerical model will be used to simulate these impacts for Oahu expressed in the contrast between the simulated current conditions and future conditions.

Principal Findings and Significance

Efforts to develop an island-wide model for the Island of Oahu are progressing towards achieving the study objectives. The islands' geology is complex and aquifers are vastly heterogeneous. To simply the development, the geology has been reduced to three hydrogeologic units: (1) dike-intruded volcanic rock, (2) dike-free volcanic rock, and (3) sediments and rejuvenated Volcanics. The altitude of the contact between overlying sediments and volcanic rock has been digitized for the entire island to 6,000 ft below sea level, which facilitated the model grid generation of the hydrogeologic units. The SWI2 model code was successfully applied to one-dimensional cross sections to test the suitability to simulate density-dependent groundwater flow in freshwater-lens aquifer systems. A one-layer island-wide model simulating dike-intruded and dike-free volcanic rock with a uniform grid-cell size of 500 ft was developed. Model calibration, currently in progress, is utilizing measured water levels, midpoint of the transition zone between fresh- and saltwater depth data, baseflow, and Pearl Harbor spring-discharge data.

This project has been merged with Project 2012HI412S: Determination of groundwater fluxes and evaluation of the effectiveness of low-permeability valley-fills in the Pearl Harbor Aquifer area, Oahu.

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Information Transfer Program Introduction

The WRRC Hawaii carries out technical transfer activities, supported in part by the USGS WRRIP, to disseminate information on research and knowledge to promote a better understanding of our water resources, problems and management options. The program allows many opportunities for researchers to interact with administrators, policy makers and the general public. WRRC's technology transfer program produces newsletters, organizes and publicizes seminars, workshops and conferences, assists in producing posters and other materials for presentations, and maintains the center's website. This aims to broaden knowledge of and appreciation for Hawaii's water resources. The Center has a dedicated Technology Transfer Specialist for this activity. These activities were scaled down this reporting year as the Specialist was on sabbatical.

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2013AS414B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	Education, None, None
Descriptors:	None
Principal Investigators:	Philip Moravcik

Publications

There are no publications.

Introduction

During the reporting period, we maintained contact with representatives from the American Samoa Power Authority (ASPA), the agency that manages the main population Center's water system, the American Samoa Environmental Protection Agency (ASEAP), and the American Samoa Community College (ASCC). The Center has ongoing research projects: *Quantifying Groundwater Discharge from the Faga'alu Aquifer, American Samoa, Building a polychaete species database for water management purposes in American Samoa, Assessing Ground Water Sustainability of the Island of Tutuila, American Samoa* in American Samoa which have moved forward despite the administrative changes at WRRC and the University of Hawaii. Discussions with ASPA, ASEPA, and ASCC to identify areas of needed research beyond those covered in these projects are ongoing. Data from WRRC's ongoing research has been provided to ASPA for potential utilization in their planning and management activities. We have also developed a training program for ASCC students that involved coordinating with a faculty member at the College. American Samoan collaborators are helping to collect project data, which has eliminated the need for Hawaii staff's repeated travel. The knowledge gained by the faculty member and the students in American Samoa will be of great benefit to their careers.

WRRC's Advisory Council includes members from American Samoa who were heavily consulted before and during proposal development and during research evolution. These members participated in a Council meeting held in 2013 through a phone conference and subsequently provided a list of research concerns for American Samoa. Despite the rocky start we expect that there will be considerable synergy between the programs in Hawaii and American Samoa. Upon his return from sabbatical WRRC's Technology Transfer Specialist will be traveling to Samoa to conduct meetings and further develop a network of contacts.

In discussions with WRRC's colleagues at the University of Hawaii Sea Grant Program it was indicated that there will be substantial changes to the composition of the Center's Advisory Council. It is planned to have greater participation of our collaborators in American Samoa on the Council. We will be convening this new Council soon.

Problem and Research Objectives

The mandate of WRRC includes an obligation to broadly disseminate the results of its research activities to audiences of local water and wastewater agencies, environmental engineering consultants, other academic researchers, and interested members of the public in American Samoa.

Methodology

The Technology Transfer Office employs a variety of techniques to disseminate the results of research conducted at the Center. The office transfers information concerning water resource research and issues to its audience through WRRC bulletins and other publications, the web site,

workshops, meetings, conferences, and regular biweekly seminars. Other activities include providing information to consultants, students of all levels, and the public, and participating in school science fairs and in research projects. The staff also regularly updates and improves the Center's web site.

Technology Transfer Program Activities

WRRC's Technology Transfer Program activities for American Samoa during the report period were aimed at further strengthening dialogue and coordinating research plans and activities with our American Samoan partners. The activities included discussions of needed research and training of students. The communications were facilitated by WRRC graduate student Christopher Schuler who has been spending a considerable amount of time in Samoa working on the WRRIP research project "Assessing Ground Water Sustainability of the Island of Tutuila, American Samoa".

WRRC workshop and travel to American Samoa

Basic Information

Title:	WRRC workshop and travel to American Samoa
Project Number:	2014AS435B
Start Date:	3/1/2014
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	Management and Planning, Law, Institutions, and Policy, Education
Descriptors:	None
Principal Investigators:	Philip Moravcik

Publications

There are no publications.

Introduction

The Water Resources Research Center at University of Hawaii only recently started to administer the State Water Resources Research Program for American Samoa (since 2013). It was proposed under this project to carry out an integrative consultation with the stakeholders of the water sector in American Samoa through a full day workshop there and related field visits. This aim was to strengthen the WRRIP program and its implementation in American Samoa by increasing awareness the program among the local stakeholders, as well as providing an opportunity for WRRC to understand the requirements and priorities of American Samoa; assessment of local research partners and opportunities. Since, the PI was on sabbatical, this work could not be carried out as proposed and will be carried out this year.

Problem and Research Objectives

The Water Resources Research Center at University of Hawaii has been administering the State Water Resources Research Program for American Samoa since last year, 2013. The administration of the fund has often been difficult as the WRRC has no firsthand knowledge of the ground realities in American Samoa and the communication with the concerned stakeholders in American Samoa requires room for improvement. Several remote telephone calls with some key players in American Samoa have been carried out, yet an integrative consultation with the stakeholders of the water sector needs to be carried out to improve the implementation of the WRRIP program and other associated water sector activities. For this purpose, it was planned to hold a full day workshop in American Samoa and a visit to water-related institutions including the community colleges, their officials and the local government representatives and to establish greater cooperation and understanding of the water and related sector in American Samoa.

The objectives of this project are establishment and enhancing linkages with the local institutions and people for a better administration of the WRRIP program, awareness of the requirements and priorities of American Samoa; as well as assessment of local research partners and opportunities. The visit to the government officials in AS, and other water related institutes and infrastructures will provide avenues for better cooperation, explore research ideas and based on the understanding of the field realities in American Samoa. The mandate of WRRC includes an obligation to broadly disseminate the results of its research activities to audiences of local water and wastewater agencies, environmental engineering consultants, other academic researchers, and interested members of the public in American Samoa.

Methodology

The proposed methodology is to deploy a 3 member team to American Samoa carry out a workshop, visit pertinent offices and sites, and enhance stakeholder participation in identifying WRRIP research needs. Informational materials about WRRC and its activities will be distributed thereby promoting their awareness about our activities. The team will also learn about

priorities and requirements from site visits, and meeting with various officials and local personnel.

The project will identify potential stakeholders and hold consultative meetings with them. A representative group, tentatively detailed below, will be invited for a workshop to bring everyone together, raise awareness and seek feedbacks on water problems, needs and priorities of American Samoa.

The PI, after his return from sabbatical, will form a group and travel to American Samoa to complete the activities under this project.

Principal Findings and Significance

The workshop and visit to American Samoa is yet to take place. After the completion of the project, it is expected that the needs and priorities of American Samoa in the water sector will be better understood and help better direct the WRRIP program there.

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2013HI413B
Start Date:	3/1/2013
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	Education, None, None
Descriptors:	None
Principal Investigators:	Philip Moravcik

Publications

1. Moravcik, Philip. 2013. Bulletin, Water Resources Research Center, University of Hawaii at Manoa (July),10 pp. http://www.wrrc.hawaii.edu/bulletins/2013/July2013bulletin.pdf
2. Moravcik, Philip. 2013. A Brief Overview of Research Conducted at Hawaii's Water Resources Research Center, University of Hawaii at Manoa (July), 8 pp. http://www.wrrc.hawaii.edu/WRRChistory.pdf
3. Moravcik, Philip. 2013. Bulletin, Water Resources Research Center, University of Hawaii at Manoa (July),10 pp. http://www.wrrc.hawaii.edu/bulletins/2013/July2013bulletin.pdf
4. Moravcik, Philip. 2013. A Brief Overview of Research Conducted at Hawaii's Water Resources Research Center, University of Hawaii at Manoa (July), 8 pp. http://www.wrrc.hawaii.edu/WRRChistory.pdf

Introduction

A small state like Hawaii allows many opportunities for researchers to interact with administrators and policy makers. In hopes of broadening knowledge of and appreciation for Hawaii's water resources, WRRC's technology transfer program produces newsletters, organizes and publicizes seminars, workshops and conferences, assists in producing posters and other materials for presentations, and maintains the center's website.

Problem and Research Objectives

The mandate of the Water Resources Research Center (WRRC) includes an obligation to broadly disseminate the results of its research activities to audiences of local water and wastewater agencies, environmental engineering consultants, other academic researchers, and interested members of the public.

Methodology

The Technology Transfer Office employs a variety of techniques to disseminate the results of research done at the Center. The office transfers information concerning water resource research and issues to its audience through WRRC bulletins and other publications, the web site, workshops, meetings, conferences, and regular biweekly seminars. Other activities include providing information to consultants, students of all levels, and the public, and participating in school science fairs and in research projects. The staff also regularly updates and improves the Center's web site.

Technology Transfer Program Activities

WRRC's Technology Transfer Program activities for the report period included: organization of multiple seminars; production of the Center newsletter; participation in meetings and conferences; and providing water-resources-research information to consultants, students of all levels, and the general public. The program PI also participated in school science fairs, research projects, and refinement of the center's web site. During the current reporting period the Technology Transfer Program produced one newsletter describing research projects and center activities and news. During this reporting period the Technology Transfer PI made extensive use of the center's large-format printer/plotter, producing posters for display at local, national, and international meetings and conferences. Two of these posters, illustrating the work of graduate student researchers, won awards at conferences.

Meetings

The Technology Transfer Office helped to organize a meeting: U.S. Recreational Water Quality Criteria: A Vision for the Future held in Honolulu, March 11–13, 2013. The Hawaii Center has a long history of involvement in the examination and investigation of recreational water quality microbial standards and has organized several previous meetings of national experts.

In December 2011, USEPA published a draft of the proposed recreational water quality criteria. This draft document indicated that the revised Recreational Water Quality Criteria (RWQC) would not differ substantially from the previous recreational water quality criteria published in 1986. However, there was a significant change in this document in that the new guidelines allow individual states to use alternative methods to monitor water quality, and to implement state-specific water quality standards. The effectiveness of these new guidelines has not been tested at the state level. Moreover, during the planning of this conference, USEPA had not yet published the guidelines for alternative methods and standards, nor finalized the proposed criteria; hence the specifics of implementation strategies as well as incentives to develop and adapt alternative standards remained unclear. For these reasons WRRC felt that science-based assessment of RWQC and discussion on how new science can be used to take advantage of the flexibilities in the new RWQC were needed. The conference focused on the use of scientific method to achieve the following goals: Evaluate the methods and approaches that were used in developing and implementing the new RWQC. Evaluate how newer methods and approaches can be used to establish site-specific criteria. Evaluate how published experimental methods can be used to determine health risk to swimmers and be applied to develop RWQC. Invited conference speakers included some of the foremost experts in the field of recreational water quality standards. They were selected based on their acknowledged expertise on the topics chosen for this conference and their demonstrated use of scientific methods in water quality research and monitoring programs. In addition to the oral presentations there were over 30 poster presentations outlining the work being done at many academic and government departments about work being done to address the shortcomings of the current system of recreational water quality monitoring. Among other work, the Technology Transfer Office produced the website for the conference. An announcement for the conference can be viewed at www.wrrc.hawaii.edu/*cleanup/rwqc2013/announce&prog.pdf.

In April WRRC hosted a workshop on advanced modeling of water flow and contaminant transport in porous media using the HYDRUS and HP1 software packages. HYDRUS is Windows-based modeling software that can be used for analysis of water flow, heat and solute transport in variably saturated porous media (e.g., soils). The HYDRUS suite of software is supported by an interactive graphics based interface for data-preprocessing, discretization of the soil profile, and graphic presentation of the results. HYDRUS has been used in hundreds, if not thousands of applications referenced in peer-reviewed journal articles and many technical reports. The software packages are also used in classrooms of many universities in courses covering soil physics, processes in the vadose zone, or vadose zone hydrology. The workshop covered a detailed conceptual and mathematical description of water flow and solute transport processes in the vadose zone. Hands-on computer sessions provided participants with an opportunity to become familiar with the software packages, including several additional modules, such as ROSETTA, HP1, UNSATCHEM, and/or the Wetlands module. Emphasis was on preparation of input data for a variety of one- and multi-dimensional applications. Advanced topics covered in the second part of the workshop included: coupled movement of water, vapor, and energy (including the surface energy balance), preferential/nonequilibrium water flow and solute transport (using dual-porosity and dual-permeability models), biogeochemical transport (using the UNSATCHEM and HP1 (coupled HYDRUS-1D and PHREEQC) modules), modeling flow and transport using a three dimensional module of HYDRUS (2D/3D)

The workshop instructor was Dr. Jirka Šimùnek from the Department of Environmental Sciences, University of California Riverside, CA. This is the third HYDRUS workshop that WRRC has sponsored.

Publication—A Brief Overview of Research Conducted at Hawaii's Water Resources Research Center

In order to educate and inform a new generation of University administrators, water agency officials, consultants, and the public the WRRC's Technology Transfer Specialist wrote and distributed an eight-page synopsis of the Center's research activities over its 50-year history. This document provides a brief background of the WRRIP program and a concise description of the kinds of research that the Hawaii center has done over the years, categorizing that research broadly into fourteen focus areas. There have been many changes to the University of Hawaii administration as well as to the personnel at local water agencies in recent years and it was felt that it would be timely to inform the newcomers about the Center's productive history.

Seminars

The Technology Transfer Program organizes biweekly seminar series designed to foster communication among WRRC researchers, students, and the organizational target audience of government agencies, private-sector researchers, and members of the general public with an interest in water-resource issues. Each semester one WRRC faculty member is appointed to recruit speakers from university faculty, visiting scientists, government agencies, and private sector firms. Topics thus vary depending on the interests of the coordinator and availability of speakers. Typically the seminars include reports on WRRC projects and discussions by government officials on emerging water-related issues. The seminars are generally well attended and provide one of the few public forums in the state for the discussion of water issues.

In response to numerous requests from individuals around our geographically isolated islands the Technology Transfer office undertook to video record and post the seminars on the internet to permit our neighbor island colleagues to benefit from our seminar presentations without the expense of travel to Honolulu. Links to the videos are now provided on the seminar listing page at the Center's website every semester.

The following is a list of the seventeen seminars presented during the reporting period.

FY 2013 Seminars

Spring 2013 Coordinator Dr. David Penn

March 6, 2013	*Introducing the Genuine Progress Indicator (GPI) to Hawaii*	Regina Ostergaard-Klem, Hawaii Pacific University, College of Natural & Computational Sciences, Global Leadership & Sustainable Development and Kirsten Oleson, University of Hawaii.
March 14, 2013	*Who are we Overlooking in Microbial Diversity Surveys and Does it Really Matter?*	Mitchell Sogin, senior scientist and director of the Josephine Bay Paul Center for Comparative Molecular Biology and Evolution, Marine Biological Laboratory in Woods Hole, Mass.

March 20, 2013	*Recovering from a Legacy of Mining in Crested Butte*	Anthony Poponi, Former Director for the Coal Creek, CO Watershed Coalition and Standard Mine Technical Advisory Group.
April 10, 2013	*Numerical Modeling of Water Flow and Solute Transport in Soils Using HYDRUS including Preferential Flow, Colloid-Facilitated Contaminant Transport, and Various Biogeochemical Processes*	Jirka Simunek, Professor and Hydrologist, Department of Environmental Sciences, University of California Riverside.
April 17, 2013	*Surface-water Availability During Low-Flow Conditions: Case study in Anahola Stream, Kaua'i, and Hawai'i Statewide Application*	Chui Ling Cheng Hydrologist, U.S. Geological Survey Pacific Islands Water Science Center.
Apr 23, 2013	*Submerged Anaerobic Membrane Bioreactor for Low Strength Wastewater Treatment*	Ng, How Yong, Associate Professor, Centre for Water Research, Department of Civil & Environmental Engineering, National University of Singapore.
May 1, 2013	*Water Planning for the Manoa Campus, University of Hawaii (UHM)*	Sharon Ching Williams, UHM Campus Architect.

Fall 2013 Coordinator Dr. Aly El-Kadi

September 5, 2013	*Updates from the State of Hawaii Environmental Health Administration, State Commission on Water Resource Management, and Honolulu Board of Water Supply*	Gary Gill, Deputy Director, Environmental Health Administration, State of Hawaii Department of Health; Roy Hardy, Hydrology Program Manager, State Commission on Water Resource Management; Glenn H. Oyama, Hydrologist-Geologist, Honolulu Board of Water Supply.
September 19, 2013	*Conservation Agriculture Production Systems (CAPS): Building Resilience into Smallholder Agriculture*	Travis Idol, Professor, Natural Resources and Environmental Management, University of Hawaii at Manoa.
October 3, 2013	*Precipitation Variability and Trend in Hawaii*	Pao-Shin Chu, Professor and State Climatologist, Department of Meteorology, University of Hawaii at Manoa.
October 17, 2013	*Submarine Groundwater Discharge Links Watershed Hydrology and Coastal Biogeochemistry*	Henrieta Dulaiova, Assistant Professor, Department of Geology and Geophysics, University of Hawaii at Manoa.
November 7, 2013	*Island Hydrology: Time to Take a Closer (and Broader) Look at Confining Structures*	Don Thomas, Director, The Center for the Study of Active Volcanoes (CSAV), University of Hawaii at Hilo.

November 21, 2013	*Modeling Specific Groundwater Problems in Hawaii: Borehole Flow and Groundwater Inundation*	Kolja Rotzoll, Department of Geology and Geophysics, University of Hawaii.
December 5, 2013	*Integrating Demand- and Supply-Side Management: Pricing and Watershed Conservation*	Kimberly Burnett, Associate Specialist, University of Hawaii Economic Research Organization.

Spring 2014 Coordinator Dr. Sayed Bateni

February 3, 2014	*The Value of an Innovative System to Process Large Volumes of Water (100 l) to Detect Microbial Pathogens in Sources of Water Used for Drinking, Recreational, Re-use, Agricultural and Food Production*	Daniel V. Lim, Ph.D.; Elizabeth A. Kearns, Ph.D., and Sonia Magaña, B.S., Advanced Biosensors Laboratory Department of Cell Biology, Microbiology, and Molecular Biology University of South Florida Tampa, Florida.
February 4, 2014	*Multi-Scale Laboratory Experimentation for Process Understanding and Up-Scaling for Field Problem Solution*	Tissa H. Illangasekare, AMAX Distinguished Chair of Civil and Environmental Engineering Director, Center for Experimental Study of Subsurface Environmental Processes Colorado School of Mines, Golden, Colorado, USA.
February 25, 2014	*Plans for World Wide Public Health Risk Assessment and Regulations for Hygienic Quality of Beach Sand and Beach Water*	João Carlos Simões Brandão, Medical Mycologist, Reference Unit for Parasitic and Fungal Infections - Department of Infectious Diseases, Instituto Nacional de Saúde/National Institute of Health.

WRRC Website

The Technology Transfer Office continually updates the departmental website (www.wrrc.hawaii.edu) with new information about WRRC researchers' activities, seminars, reports, meetings, grant announcements, and the Center's L. Stephen Lau scholarship fund. The site provides information about center facilities and personnel as well as a database of WRRC publications. A web-site search function provides easy access to the available information.

As mentioned above we are now recording and posting center seminars on the internet to permit distant colleagues the opportunity to see our seminars from their home islands. Links to these videos are provided on the seminar webpages. For example: www.wrrc.hawaii.edu/spring2014seminars.shtml. We have added an RSS feed to the home page (www.wrrc.hawaii.edu) that aggregates water news from a variety of sources including the technology transfer offices own blog. This adds a more dynamic feel to the Center's website.

Digitization and Online Posting of Center Publications

The technology transfer office continues to add publications to the University of Hawaii at Manoa's ScholarSpace institutional repository database. Several years ago the Technology Transfer Office initiated the digitization of the Center's large archive of reports generated by the many projects conducted at the Center over the past 40 years. These reports are available for downloading in PDF format at the ScholarSpace website (http://scholarspace.manoa.hawaii.edu/). Previously, individuals wanting to access the information in these reports would have to write to WRRC and request to have a copy mailed to them for a cost. This initiative represents a substantial milestone in our efforts to disseminate the results of our Center's research. Following a decision by our past director WRRC no longer publishes reports in-house and our researchers submit their reports as articles directly to journals which generally restrict access to these articles. WRRC continues to post the abstracts and publication information about these articles on our website.

Poster Production

The Technology Transfer Program PI assisted numerous center faculty and graduate research assistants in the design and production of posters illustrating research projects for display at meetings and conferences. Three graduate-research-assistant posters were recognized by conference awards.

Media Contact

During the reporting period the Technology Transfer project P.I. responded on several occasions to inquiries from reporters about water and environmental issues. In addition the Technology Transfer Office submitted news releases regarding the research activities of Center faculty to local and national media through the University of Hawaii's media office.

Editing of Research Articles, Reports, Proposals

WRRC's Technology Transfer Specialist provided editorial services for numerous reports and articles during the reporting period. This work helps to disseminate the Center's research results through journals and other publications.

L. Stephen Lau Scholarship

The Technology Transfer Office took responsibility again this year for coordinating the announcement, application review, applicant selection for the Center's L. Stephen Lau Scholarship. This scholarship is made annually thanks to an endowment by former WRRC Director L. Stephen Lau and his wife.

Committee to Select WRRIP 104b Grantees

The Technology Transfer Specialist at WRRC served on the committee to review and select for funding proposals made under the WRRIP 104b program.

The Center's Advisory Council

The center convenes a council of local water stakeholders in Hawaii and Samoa in order to help guide our research priorities. No meeting of this group was held during the reporting period however we continue to maintain contact with the council members in anticipation of our next meeting.

Members of the Center's Advisory Council include:

Name/Title	**Agency**
Ernest Lau, Manager and Chief Engineer	Honolulu Board of Water Supply
Ross Tanimoto, Deputy Director	Department of Environmental Services, City and County of Honolulu
Debbie Solis, Program/Project Manager - Civil Works staff	U. S. Army Corps of Engineering
Roy Hardy	State of Hawaii, Commission on Water Resource Management
Thomas Matsuda, Program Manager, Pesticide Branch	Hawaii Department of Agriculture
J. Mark Ingoglia, Chief, Environmental Branch	HQ PACAF, US Airforce
Scott McAdam, President, HWEA Hawaii Section	Hawaii Water Environment Association
Richard Cox	Private Citizen, former Water Commissioner
Stephen Anthony, Director,	USGS Pacific Islands Water Science Center
Dayan Vithanage	Oceanit Inc. consultants in Honolulu
For American Samoa	
Daniel Aga, Dean and Director of Community and Natural Resources Division	American Samoa Community College
Robert Kerns, Senior Environmental Engineer	American Samoa Power Authority
Jason Gambatese, Program Manager	USEPA Region 9
Faamao Asalele, Jr., Asst. Director	American Samoa EPA

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2014HI426B
Start Date:	3/1/2014
End Date:	2/28/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	Education, None, None
Descriptors:	None
Principal Investigators:	Philip Moravcik

Publications

There are no publications.

Technology Transfer

The mandate of the Water Resources Research Center (WRRC) includes an obligation to broadly disseminate the results of its research activities to audiences of local water and wastewater agencies, environmental engineering consultants, other academic researchers, and interested members of the public. The Center also invites other experts to give talks and presentations to which a large number of people from the government, local agencies, academia, students and the public are invited to attend.

Methodology

The Technology Transfer Office employs a range of media to disseminate the results of research done at the Center and around in Hawaii. WRRC bulletins; other publications; web site; workshops, meetings, and conferences; and regular biweekly seminars all served to aid the center in transferring information concerning water-resource research and issues to its audience. WRRCs Technology Transfer program included a seminar series, participation in conferences, assistance to consultants, students of all levels, and the public, participation in school science fairs, direct participation in research projects having an informational component, and maintenance and expansion of the Center's web site. Major activities conducted by the Technology Transfer Office included the following:

Seminars

One of the principal activities of the Technology Transfer Office is the organization of the Center's seminar series. As it has done for more than twenty years, the Technology Transfer Program continues to organize biweekly seminars during the Fall and Spring academic sessions. It is designed to foster communication among WRRC researchers, students, and the organizational target audience of government agencies, private-sector researchers, and members of the general public with an interest in water resource issues. Each semester, one WRRC faculty member is appointed to organize the seminars with the assistance of the Technology Transfer office, and recruit speakers from university faculty, visiting scientists, government agencies, and private sector firms. Topics thus vary depending on the interests of the coordinator and availability of speakers. Typically the seminars include reports on WRRC projects and discussions by government officials on emerging water-related issues. The seminars are generally well attended and provide one of the few public forums in the state for the discussion of water issues.

This reporting period, Dr. Roger Babcock was the coordinator for the 2014 Fall Seminar Series and Dr. Laxman Sharma took care of the 2015 Spring Seminar Series. Also from this year, the Technology Transfer Office began a new initiative to record video of the seminars and post these videos on the internet with links on our web-page to accommodate potential audiences who could not be physically present at the seminar. The videos are accessible through the Center's

seminar webpage. The following is a list of the twelve seminars presented during the reporting period.

FY 2014 Seminars

Spring 2014 Seminars

Mar. 4, 2014	*Ecological Sanitation in Urine Diverting (UD) Mode to: Conserve Water and Energy, Recover Nutrients, and Reduce Estrogen Pollution*	Krishna Lamichhane, Graduate Researcher, University of Hawaii
Mar. 18, 2014	*Lidar Remote Sensing of Land Surface: Implications for Ecohydrology*	Qi Chen, Ph.D., Professor of Geography, University of Hawaii at Manoa
Apr. 1, 2014	*Evaluation of Suomi NPP VIIRS Vegetation Index EDR via Product Inter-comparison with Aqua MODIS*	Tomoaki Miura, Associate Professor, Natural Resources and Environmental Management, University of Hawaii at Manoa
Apr. 22, 2014	*Building an Ecosystem Service Tool to Support Ridge-to-Reef Management and Conservation in Hawaii*	Kirsten L.L. Oleson (and lab), Assistant Professor, Natural Resources and Environmental Management, University of Hawaii at Manoa
May 6, 2014	*A Case Study of a Sustainable, Dynamic, and Cost-Effective Approach to the Remediation of a Petroleum-Impacted Site*	Sergio Cocchia, Project Manager and Environmental Engineer/Geologist, CH2M Hill

Fall 2014 Seminars

Oct. 9, 2014	*The Future of Wastewater in Honolulu*	Timothy Houghton, Deputy Director, Dept. of Environmental Services, City & County of Honolulu
Oct. 23, 2014	*Future Trends for Drinking Water in Honolulu*	Barry Usagawa, Program Administrator, Water Resources Division, Honolulu Board of Water Supply
Nov. 20, 2014	*Honouliuli WWTP Facility Upgrades to Meet Full Secondary Requirements by 2024*	Jordan Fahmie, Engineer, AECOM
Nov. 25, 2014	*Sand Island Wastewater Treatment Plant: from 1976 to today and on to 2035*	Tiow Ping Wong, Senior Environmental Engineer, R.M. Towill Corp.

Spring 2015 Seminars

Feb. 5, 2015	*An Inventory of Sedimentation in Hawaii's Reservoirs*	Kim Falinski, PhD Candidate, Department of Tropical Plant and Soil Sciences, CTAHR, UH Manoa
Feb. 5, 2015	*Mitigating the Effects of Urbanization with Bioretention Rain Gardens*	Amanda Cording, PhD Candidate, Department of Plant and Soil Science, University of Vermont, Burlington, Vermont
Feb. 19, 2015	*Development of Modeling-based Decision Support Tools for Managing Impacts of Climate Change and Invasive Species on Tropical Forest Watersheds*	Christian P. Giardina, PhD, Research Ecologist, Forest Service, Institute of Pacific Islands Forestry, Hilo, Hawaii

WRRC Website

The Center's website (www.wrrc.hawaii.edu) is continually updated with new information about WRRC researchers' activities, seminars, reports, meetings, grant announcements, scholarship opportunities, etc. The site provides information about center facilities and personnel as well as access to a database of WRRC publications. A search function provides easy access to the available information. There is a link on the Center's home page that leads to an archive of full-text PDF files of reports written by WRRC researchers since the early days of the Center. This permits extremely easy access to our reports for our clientele. Following a decision by our past director WRRC no longer publishes reports in-house and our researchers submit their reports as articles directly to journals which generally restrict access to these articles. WRRC continues to post the abstracts and publication information about these articles on our website. During the reporting period we also established a Twitter account to notify people about upcoming seminars and other events.

Poster Production

The Program assisted numerous center faculty and graduate research assistants in the design and production of posters illustrating research projects for display at meetings and conferences. Several graduate-research-assistant posters were recognized by conference awards during the reporting period.

Media Contact

During the reporting period the Technology Transfer project P.I. responded on several occasions to inquiries from reporters about water and environmental issues. In addition the Technology Transfer Office submitted news releases regarding the research activities of Center faculty to local and national media through the University of Hawaii's media office.

L. Stephen Lau Scholarship committee

The Technology Transfer Office took responsibility again this year for coordinating the announcement, application review, applicant selection for the L. Stephen Lau Scholarship. This scholarship is made annually thanks to an endowment by former WRRC Director L. Stephen Lau and his wife Mrs. Virginia Lau.

Oversight of Center publications staff

The Technology Transfer Office provides oversight of the Center's publications staff, which assist faculty with layout and production of articles and reports.

Editing

WRRC's Technology Transfer Specialist provided editorial services for a number of reports, proposals, and articles during the reporting period. This work helps to disseminate the Center's research results through journals and other publications.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	0	0
Masters	2	0	0	0	2
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	1	1
Total	4	0	0	1	5

Notable Awards and Achievements

2012HI355B: $35,000 support from Clean Water Branch (Hawaii Department of Health) for a microbial source tracking study in the Kahaluu watershed.

2011HI318B: Beilman, D.W. and O. Elison-Timm, 2015, NSF Proposal 1502984, Collaborative Research: data-model comparison of Holocene Pacific hydroclimate variability in the Hawaiian Islands using geochemical records and SynTraCE-21 simulations, $359,200. Recommended for funding, begins 7/1/2015.

2013AS424B: New award - Assessing Sustainability of Ground Water Resources Under Future Climate Conditions, NOAA through The East West Center, $105,625, 2014.

Publications from Prior Years

1. 2014HI428B ("Evaluation of Portable Multi-use Automated Concentration System (PMACS) for the analysis of indicator bacteria and microbial source tracking markers in Hawaii") - Conference Proceedings - Kirs, M., Kearns, E. A., Magaña, S., Lim, D. V., Fujioka, R. 2014. Detection and quantification of microorganisms in recreational and potable water in Hawaii by high-volume ultrafiltration method. In proceedings of the AWWA Water Quality and Technology Conference, November 16-20 New Orleans, Louisiana.
2. 2011HI318B ("Long-term aspects of high-elevation rainfall and climate change, O") - Articles in Refereed Scientific Journals - Schubert, O.S., S. Pau, S. Hotchkiss, and D.W. Beilman. Reconstruction of Holocene environmental change at a windward site in the Hawaiian Islands. The Holocene (in preparation).
3. 2011HI318B ("Long-term aspects of high-elevation rainfall and climate change, O") - Dissertations - Schubert, Olivia, 2012, “Vegetation reconstruction of Kaau Crater through the Holocene (MA Thesis)” Department of Geography, University of Hawaii, Honolulu, HI, 85 pp.
4. 2012HI362B ("Fate and Transport of Pharmaceutically Active Compounds in Simulated Bank Filtration System") - Conference Proceedings - D’Alessio, M., and C. Ray, 2013, "Environmental Fate and Transport of Selected Pharmaceutically Active Compound during Riverbank Filtration", presented at 2013 World Environmental and Water Resources Congress, Cincinnati, OH, USA, May 19-23.
5. 2012HI362B ("Fate and Transport of Pharmaceutically Active Compounds in Simulated Bank Filtration System") - Articles in Refereed Scientific Journals - D’Alessio M., B. Yoneyama, and C. Ray , 2015. "Fate of selected pharmaceutically active compounds during simulated riverbank filtration", Science of the Total Environment, 505: 615–622.